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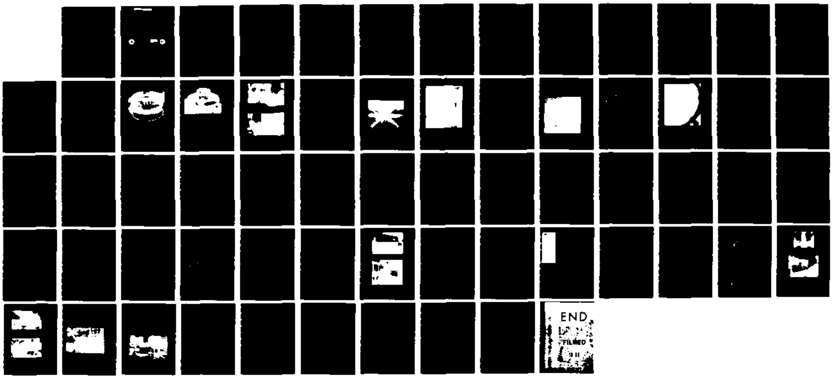

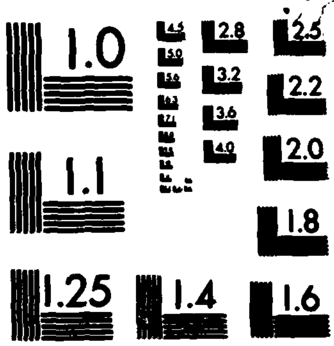

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EVALUATION OF FEDERAL AVIATION ADMINISTRATION ENGINE EXHAUST SAMPLING RAKE

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[redacted]

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FINAL REPORT

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16. Abstract (Federal Aviation Administration)

A FAA exhaust emissions rake was tested in the Experimental Clean Combustor Program, Phase III to permit comparison of the values of gaseous emissions and smoke measured by the FAA rake with those measured with the NASA/P&WA rake used in the Phase III Experimental Clean Combustor Program and with station 7 probes. The results showed that the levels of CO, THC, NO_x and smoke measured by the FAA and NASA/P&WA rakes agree well at high power, but that CO emissions measured by the FAA rake were approximately 10 percent higher than those measured by the NASA/P&WA rake at low power.

17. Key Words (Suggested by Author(s)) Emissions Standards; Vorbix Combustor	18. Distribution Statement Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161. Unclassified - STAR Category 45

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FOREWORD

This document describes the work performed by the Commercial Products Division, Pratt & Whitney Aircraft Group of United Technologies Corporation under the Federal Aviation Administration Addendum to Phase III of the Experimental Clean Combustor Program. This final report was prepared for the Federal Aviation Administration in compliance with the requirements of Modifications No. 2 and No. 3 to National Aeronautics and Space Administration Lewis Research Center Contract NAS3-19447. This report has been assigned Commercial Products Division, Pratt & Whitney Aircraft Group internal report number PWA-5534.

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SUMMARY

The Federal Aviation Administration Rake Evaluation Program was conducted concurrently with, and as an addendum to, the NASA/P&WA Experimental Clean Combustor Program (ECCP), Phase III, during the last quarter of 1976. The objective was to compare the levels of gaseous emissions and smoke measured by the Federal Aviations Administration (FAA) rake with those measured by the National Aeronautics and Space Administration (NASA)/ Pratt & Whitney Aircraft (P&WA) rake that was used to sample engine exhaust during the Phase III Experimental Clean Combustor Program and with Station 7 probes.

This program was accomplished in four tasks: Task I, Testing and Data Acquisition at a minimum of six power settings to establish a baseline using the National Aeronautics and Space Administration/Pratt & Whitney Aircraft cruciform rake; Task II, Installation of the FAA supplied rake on the engine tailpipe; Task III, Test and Data Acquisition at a minimum of ten test points including those conducted during Task I; and Task IV, Analysis of the Data and reporting.

The Federal Aviation Administration sponsored engine tests were conducted in a manner similar to that of other JT9D experimental engines at Pratt & Whitney Aircraft. Test stand inlet conditions were not artificially controlled so that the engine was run with various ambient temperature and barometric conditions and rarely on a "standard" day. Engine performance parameters were corrected to standard day conditions. Since the program was directed toward measurement of emissions at specific power levels, the steady state emissions data were taken for most points by establishing combustor inlet temperature level, regardless of ambient conditions. The emission data were corrected from the observed combustor inlet conditions to the corresponding standard day reference conditions for presentation in this report.

Under this addendum, approximately 6 hours of engine testing were conducted, consisting of 1.5 hours of emission acquisition with Station 7 probes and the NASA/P&WA 24-point channel rake and 4.6 hours of emissions acquisition with the Station 7 probes and the FAA exhaust emission rake. Both emission tests were conducted with the two-stage Vorbix combustor installed in experimental JT9D engine X-686.

The principal conclusions derived from this work are:

- The CO, THC, NO_x, and smoke data obtained from the FAA and NASA/P&WA rakes agree well at high power.
- At low power levels (idle and approach), the CO emissions measured by the FAA rake were approximately 10 percent higher than those measured by the NASA/ P&WA rake.
- The FAA rake evaluated in this program produces measurable tailpipe blockage and consequent engine performance shifts. The performance shifts had negligible affect on setting engine conditions and did not impact emission measurements.

INTRODUCTION

The objective of this addendum to the Phase III Experimental Clean Combustor Program (Reference 1) was the evaluation of a Federal Aviation Administration-supplied engine exhaust sampling rake installed behind an experimental JT9D engine. The Federal Aviation Administration rake is diamond shaped and is attached directly to the core engine tailpipe with its sampling plane 3 inches downstream of the tailpipe exit. This rake design has been used to measure emission from several aircraft gas turbine engines in the field including the Pratt & Whitney Aircraft low-bypass JT3D and JT8D models and the core exhaust of the JT9D.

This addendum utilized the large amount of data generated in the Experimental Clean Combustor Program for a "low emissions" type two-stage Vorbix combustor using an 8-arm rake mounted 14-inches back of the tailpipe free of the engine and compare with the data collected using the Federal Aviation Administration rake for this type of combustor. The data collected by both the National Aeronautics and Space Administration and the Federal Aviation Agency rakes were compared with the data collected from probes which are normally used to measure turbine exit total pressure.

A summary of the program plan and schedule is provided in Chapter I. Chapter II contains a description of the reference engine (JT9D-7A) and gas sampling rakes used in this program; and a description of the test and analyses procedures. The program results are discussed in Chapter III and concluding remarks are presented in Chapter IV. Additional information concerning equipment and experimental procedures is contained in Appendix A. Experimental data are tabulated in Appendix B. References are provided in Appendix C.

CHAPTER I

PROGRAM DESCRIPTION

A. PHASE III EXPERIMENTAL CLEAN COMBUSTOR PROGRAM

The Phase III program, recently completed, consisted of a detailed evaluation of a low pollution combustor and associated fuel system components in a JT9D engine. The test program included steady-state pollution and performance evaluations, as well as transient acceleration and deceleration engine operation. Details of the Phase III work are contained in Reference 1.

B. EVALUATION OF FEDERAL AVIATION ADMINISTRATION ENGINE EXHAUST SAMPLING RAKE

The Federal Aviation Administration Rake Evaluation Program was conducted concurrently with, and as an addendum to, the Experimental Clean Combustor Program (ECCP) Phase III contract during the last quarter of 1976. The object of this addendum was to provide the experimental data and analysis whereby the levels of gaseous emissions and smoke measured by the Federal Aviation Administration (FAA) rake could be compared to the National Aeronautics and Space Administration/Pratt & Whitney Aircraft rake that was used to sample engine exhaust during the Phase III Experimental Clean Combustor Program and with Station 7 probes.

This program was accomplished in four tasks: Task I, Testing and Data acquisition at a minimum of 6 power settings to establish a baseline using the National Aeronautics and Space Administration/Pratt & Whitney Aircraft cruciform rake; Task II, installation of the Federal Aviation Administration supplied rake on the engine tailpipe; Task III, testing and data acquisition at a minimum 10 test points including those conducted during Task I; and Task IV, the analysis of the data and reporting.

C. PROGRAM SCHEDULE

The Experimental Clean Combustor Program schedule with the Federal Aviation Administration/Pratt & Whitney Aircraft Rake Evaluation Program is presented in Figure 1 along with the overall Phase III Experimental Clean Combustor Program.

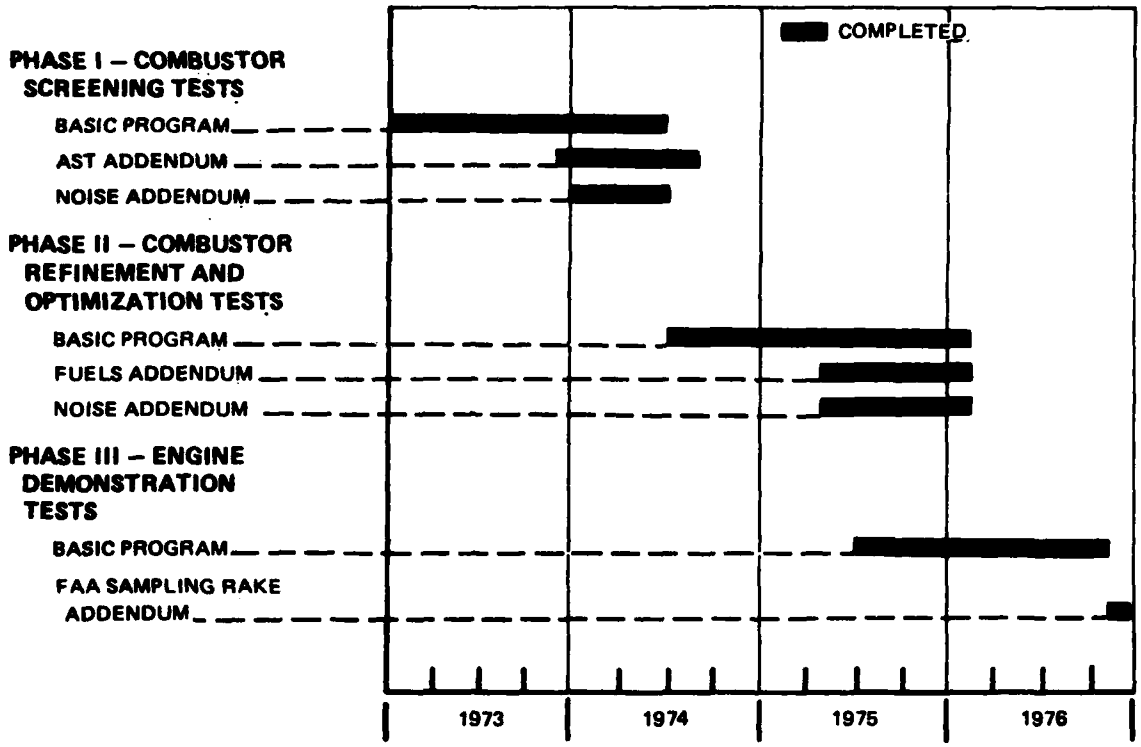


Figure 1 The Experimental Clean Combustor Program Schedule With the Federal Aviation Administration/ Pratt & Whitney Aircraft Rake Evaluation Program

CHAPTER II

EQUIPMENT AND EXPERIMENTAL PROCEDURES

A. TEST COMBUSTOR

A cross section drawing of the Phase III Vorbix (vortex burning and mixing) combustor is shown in Figure 2. A front view of the pilot fuel system arrangement and the circumferential location of the pilot and main fuel injectors is shown in Figure 3. Figure 4 presents a photograph of the outer combustor liner and head assembly after installation of the hood. The inner combustor liner is shown in Figure 5 mounted on the instrumented first-stage turbine vane assembly.

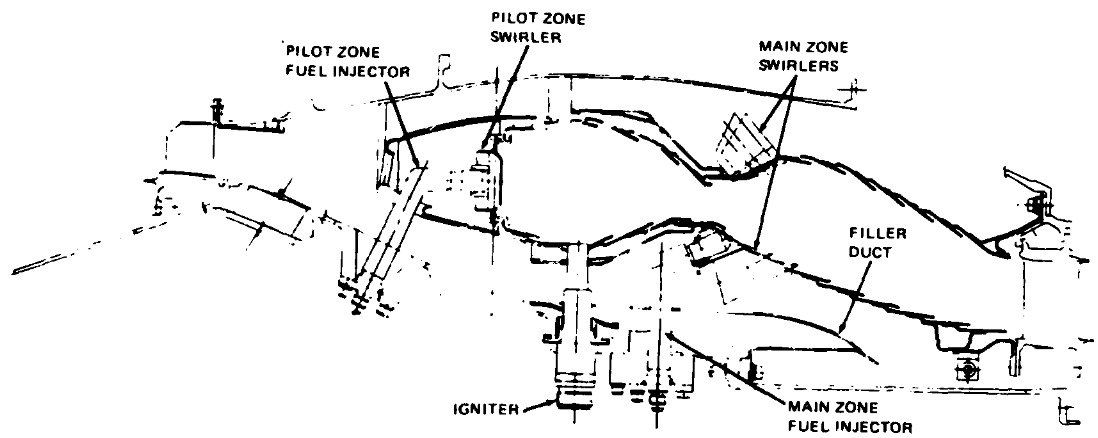


Figure 2 Cross Section of Experimental Clean Combustor Program Phase III Vorbix Combustor

The vorbix concept incorporates two burning zones separated axially by a high velocity throat section. The pilot zone is a conventional swirl-stabilized, direct-injection combustor employing thirty fuel injectors. It is sized to provide the required heat release rate for idle operation at high efficiency. Emissions of carbon monoxide and unburned hydrocarbons are minimized at idle operating conditions primarily by maintaining a sufficiently high pilot zone equivalence ratio to allow complete burning of the fuel.

At high power conditions, the pilot exhaust equivalence ratio is reduced as low as 0.3 (including pilot dilution air) to minimize formation of oxides of nitrogen. The minimum equivalence ratio for the pilot zone is determined by the overall lean blowout limits, combustion efficiency, and the need to maintain sufficient pilot zone temperature to vaporize and ignite the main zone fuel. Main zone fuel is introduced through fuel injectors located at the outer wall of the liner downstream of the pilot zone discharge location. Sixty fuel injectors are used. Main zone combustion and dilution air is introduced through sixty swirlers positioned on each side of the combustor (120 total).

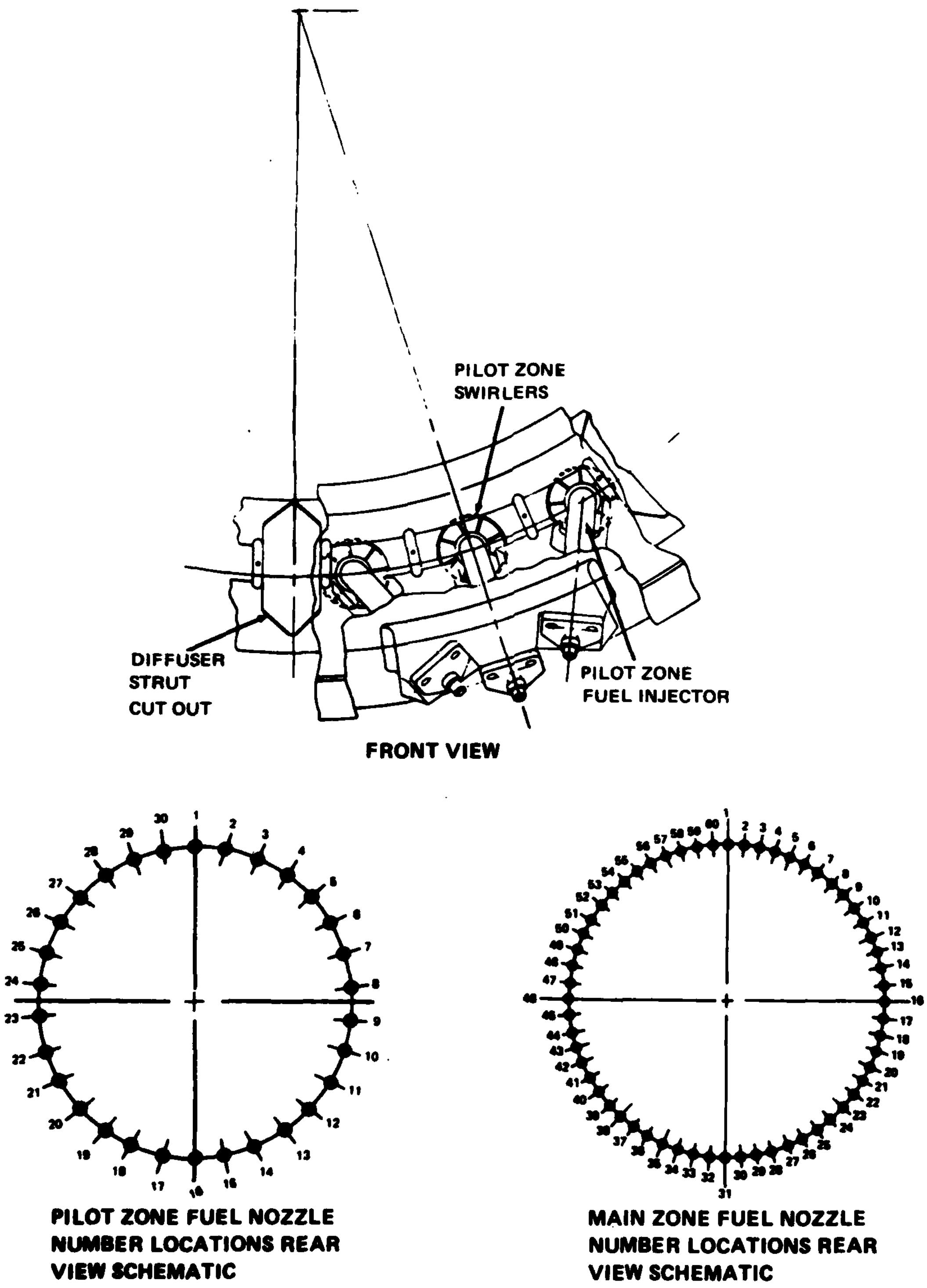


Figure 3 Vorbix Combustor Fuel Injector Arrangement

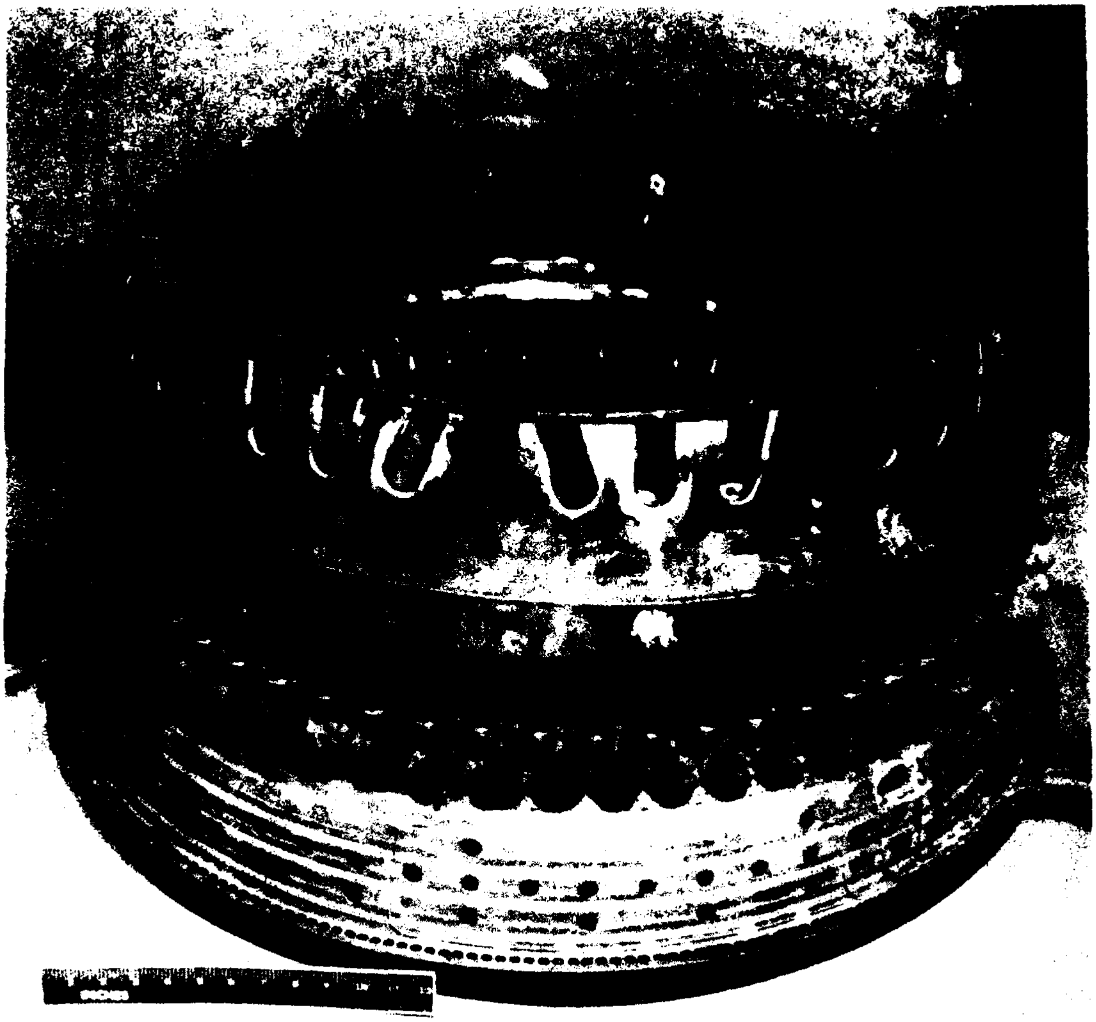


Figure 4   Phase III Vorbix Outer Combustor Liner (XPN-59997)

Figure 5 Phase III Vorbix Inner Combustor Liner on First-Stage Turbine Vane Assembly (XPN-59678)

B. EXPERIMENTAL ENGINE X-686 DESCRIPTION

Engine Configuration

Experimental JT9D-20 engine X-686 was designated as the test vehicle for the Phase III Experimental Clean Combustor Program. The JT9D-20 engine model is equivalent to the JT9D-7A reference engine in gas generator configuration and performance. The major differences between the two models are the locations of the mounting attachment points, accessory gearbox, and other external components. The JT9D-20 model is preferred to combustor development work because the gearbox is located forward and away from the combustor case. The design of experimental fuel manifolds and instrumentation is considerably simplified by removal of the JT9D-7 envelope constraints, and the external components are easily accessible for service. The engine was operated at JT9D-7A combustor inlet parameters and thrust levels for the Phase III test program.

Figures 6 and 7 show external views of engine X-686 prior to the start of Phase III testing. The two-stage Vorbix external fuel system is visible, as is the first-stage turbine inlet guide vane Automatic Recording Temperature System (ARTS) instrumentation package.

Figure 6 Experimental JT9D-20 Engine X-686 With Vorbix Combustor and ARTS Instrumentation Ready for Initial Test – Right Side (CN-57359)

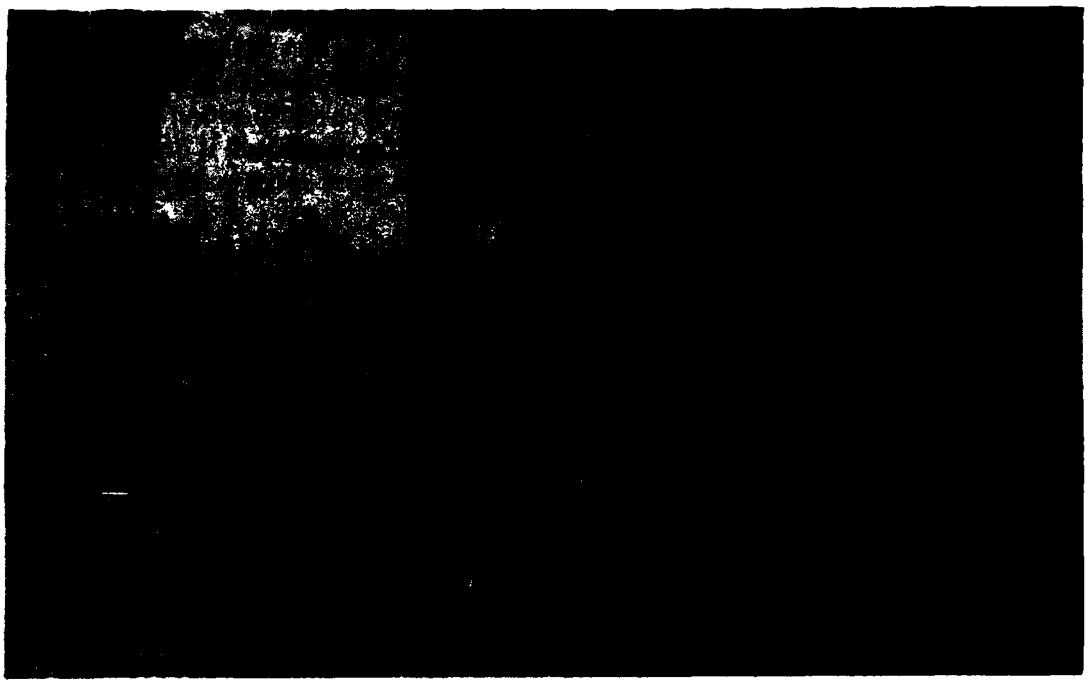


Figure 7 Experimental JT9D-20 Engine X-686 With Vorbix Combustor and ARTS Instrumentation Ready for Initial Test – Left Side (CN-57360)

Performance Instrumentation

In order to compute overall performance characteristics, experimental engine X-686 was instrumented to measure the following engine operating parameters.

- Engine inlet temperature – T_{t2}
- Low rotor speed – N_1
- High rotor speed – N_2
- Gearbox breather pressure – P
- Gearbox breather temperature – T
- Engine thrust F_N
- Engine inlet total pressure – P_{T2}
- Fan discharge total pressure – $P_{t2.5}$
- Engine exit total pressure – P_{t7}
- High turbine discharge temperature – T_{t6}
- Engine exit total temperature – T_{t7}
- Burner pressure – P_{s4}
- Total engine fuel flow – W_f

In addition, pressure and temperature probes were added to the compressor discharge station to measure combustion inlet conditions; extensive instrumentation (total and static pressure taps) was added to the diffuser/combustor section to establish airflow distribution into the combustor; thermocouples were installed at critical locations on the combustor liner skin for monitoring these areas and gas samples were withdrawn through taps at the downstream end of the ID and OD diffuser shroud passages and passed through a hydrocarbon analyzer to detect internal fuel leakage, fuel aspiration, or combustor damage should it occur. The engine and combustor section instrumentation is described in more detail in Appendix A.

P-6 Test Stand

All engine testing under the Phase III Experimental Clean Combustor Program was conducted at the Pratt & Whitney Aircraft production test facility in Middletown, Connecticut. This facility includes a series of ambient inlet, indoor test cells with sufficient cell volume and flow capacity to test high airflow engines in the JT9D thrust class. The P-6 test stand has been equipped with the additional instrumentation and data handling capability required for ARTS and low-emission combustor development programs. A description of the test stand and data acquisition system is given in Appendix A.

C. EXHAUST GAS SAMPLING INSTRUMENTATION

Three gas sampling techniques were used to obtain the engine exhaust emission data during this program.

The primary means of exhaust gas sample acquisition during the Phase III Experimental Clean Combustor Program was a rake assembly having eight radial arms spaced at 45 degree intervals mounted in the core engine exhaust stream 0.36m (14 inches) downstream of the exhaust nozzle exit plane. The unmounted rake shown in Figure 8 was designed for use with a JT9D experimental tailpipe (cylindrical section). Twenty-four sampling ports are located on eight radial arms at the center of equal areas. All 24 ports were manifolded together while the sampling rake was kept stationary in a support frame mounted in the P-6 engine test cell as shown in Figure 9.

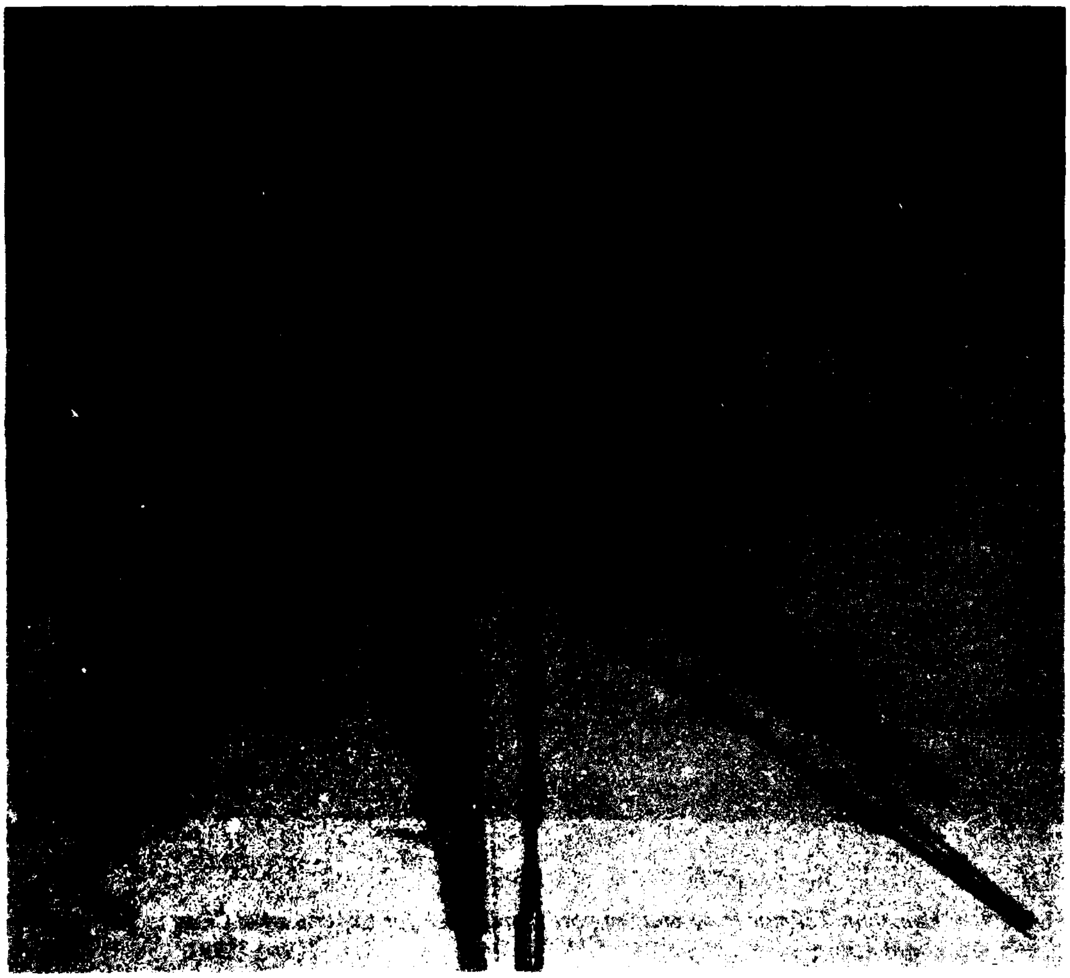


Figure 8 Primary Exhaust Rake for Experimental Clean Combustor Program Phase III Test Program (XPN-59484)

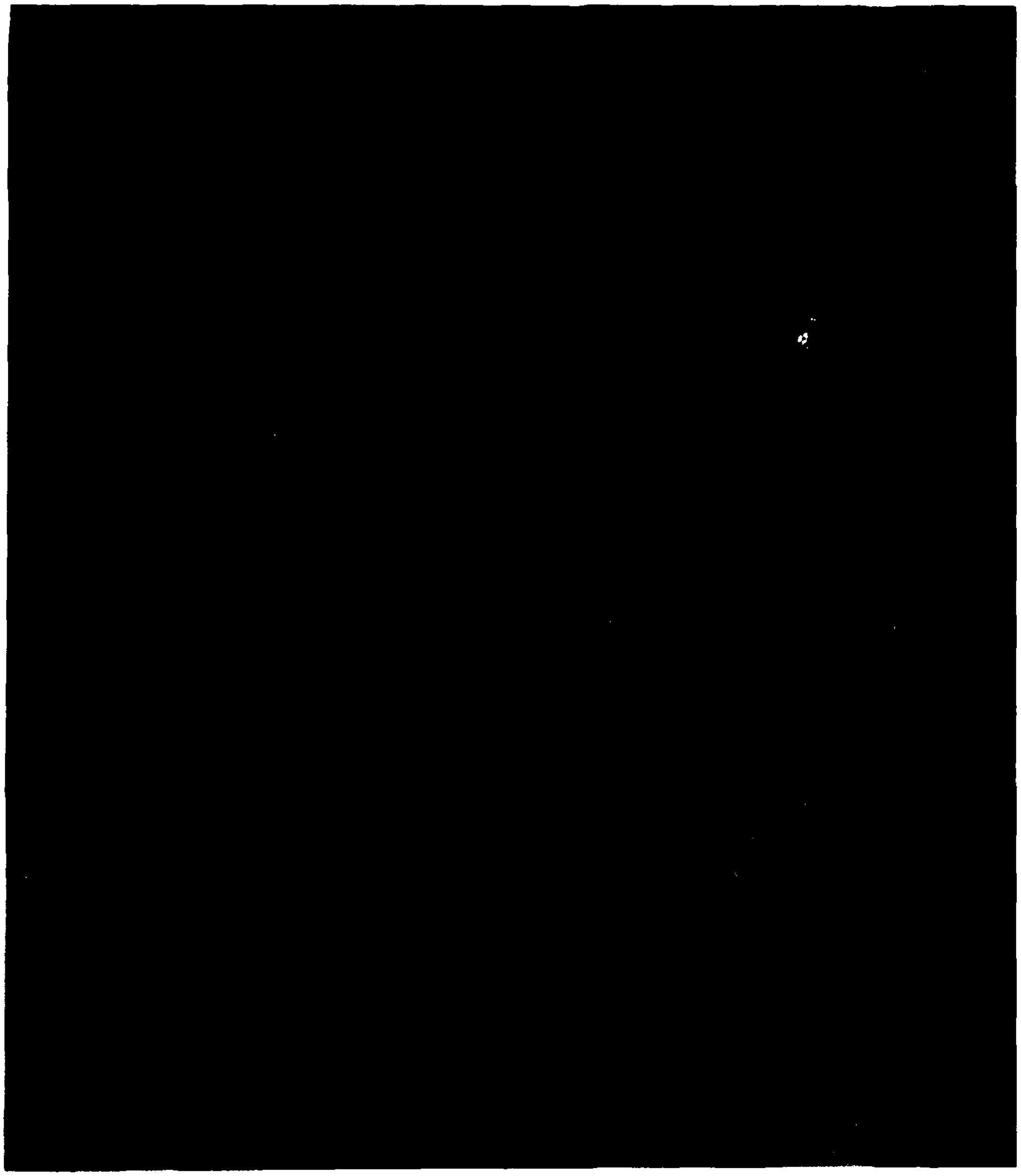


Figure 9 Emissions Tailpipe Rake and Support Frame Used for Experimental Clean Combustor Program Phase III (CN-57539)

An additional exhaust gas sampling system utilized for comparison purposes in this program as well as in the Phase III test programs [Reference 1], consisted of the standard production engine exhaust total pressure probes. These were six Station 7 pressure probes each with 8 radial pressure taps manifolded to deliver a single gas sample to the analysis equipment. The circumferential and radial positions of the sampling ports are shown in Figure 10.

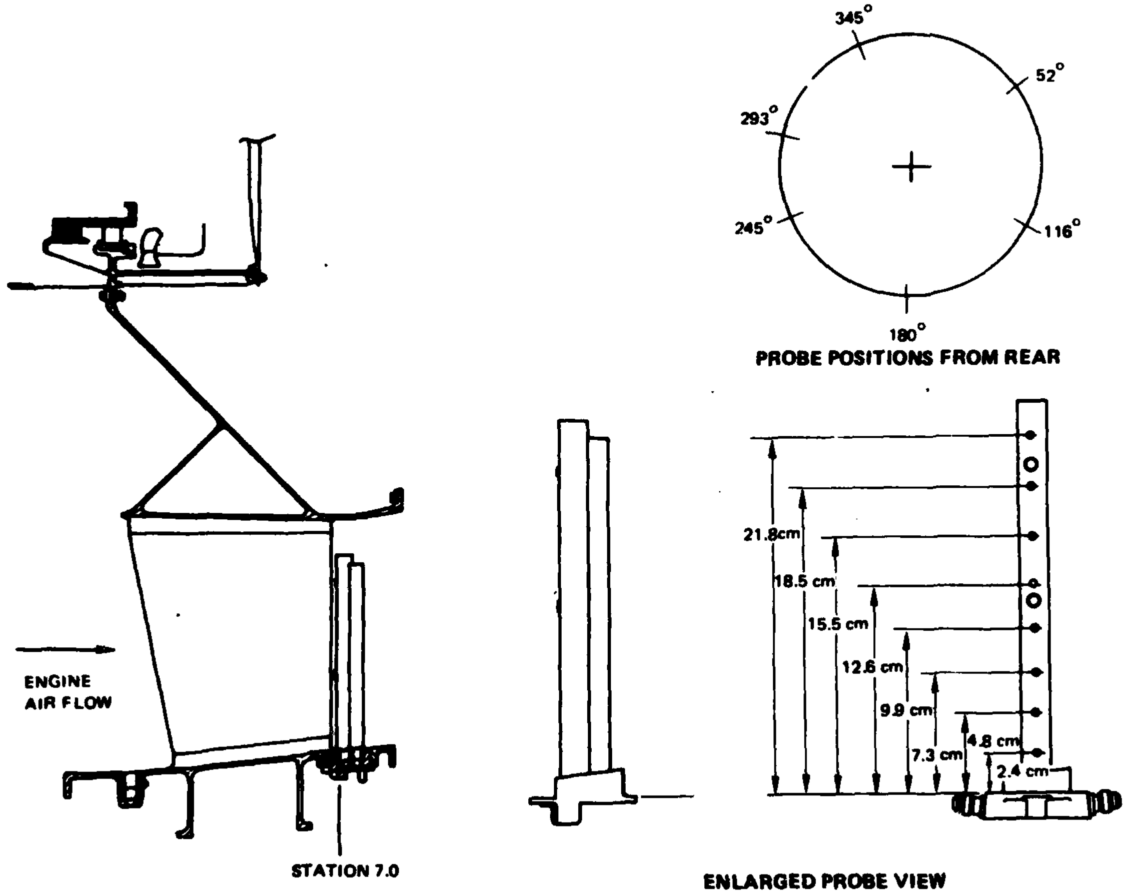


Figure 10 Station 7 Gas Sample Probe Array Used in the Experimental Clean Combustor Program and in the Federal Aviation Administration Test Program

The Federal Aviation Administration supplied rake, shown in Figure 11, was intended for use on an installed aircraft gas turbine engine with nacelle. The diamond configuration was designed to clear the exhaust nozzle centerbody, common to several nacelle installations, including the JT9D. The diamond rake evaluated in this program was sized to fit the cylindrical tailpipe (no centerbody) normally used in JT9D experimental engine testing. Each side of the diamond shaped rake contains three sampling ports of equal size (approximately 8.99 mm (0.035 inch) diameter) manifolded to a single heated line. The typical arrangement recommended by the Federal Aviation Administration for locating and securing the sampling probe to the exhaust nozzle is shown diametrically in Figure 12. This arrangement enables concentric placement of the probe with the exhaust nozzle with allowance for radial thermal

expansion and minimal interference with the nozzle flow area. The assembly is positioned on the nozzle rim with four equispaced mounting pads and secured with four tension rods between the thrust reverser forward shroud and the torsional support ring attached to the clevis pieces. Thermal expansion of the exhaust nozzle is taken up by compression of springs at the aft end of the tension rods. The complete rake installation on the experimental engine used in this program, shown in Figure 13, resulted in the sampling plane being located approximately 7.62 cm (3 inches) downstream of the tailpipe exit.

A detailed description of the gas analysis and conditioning equipment is presented in Appendix A.

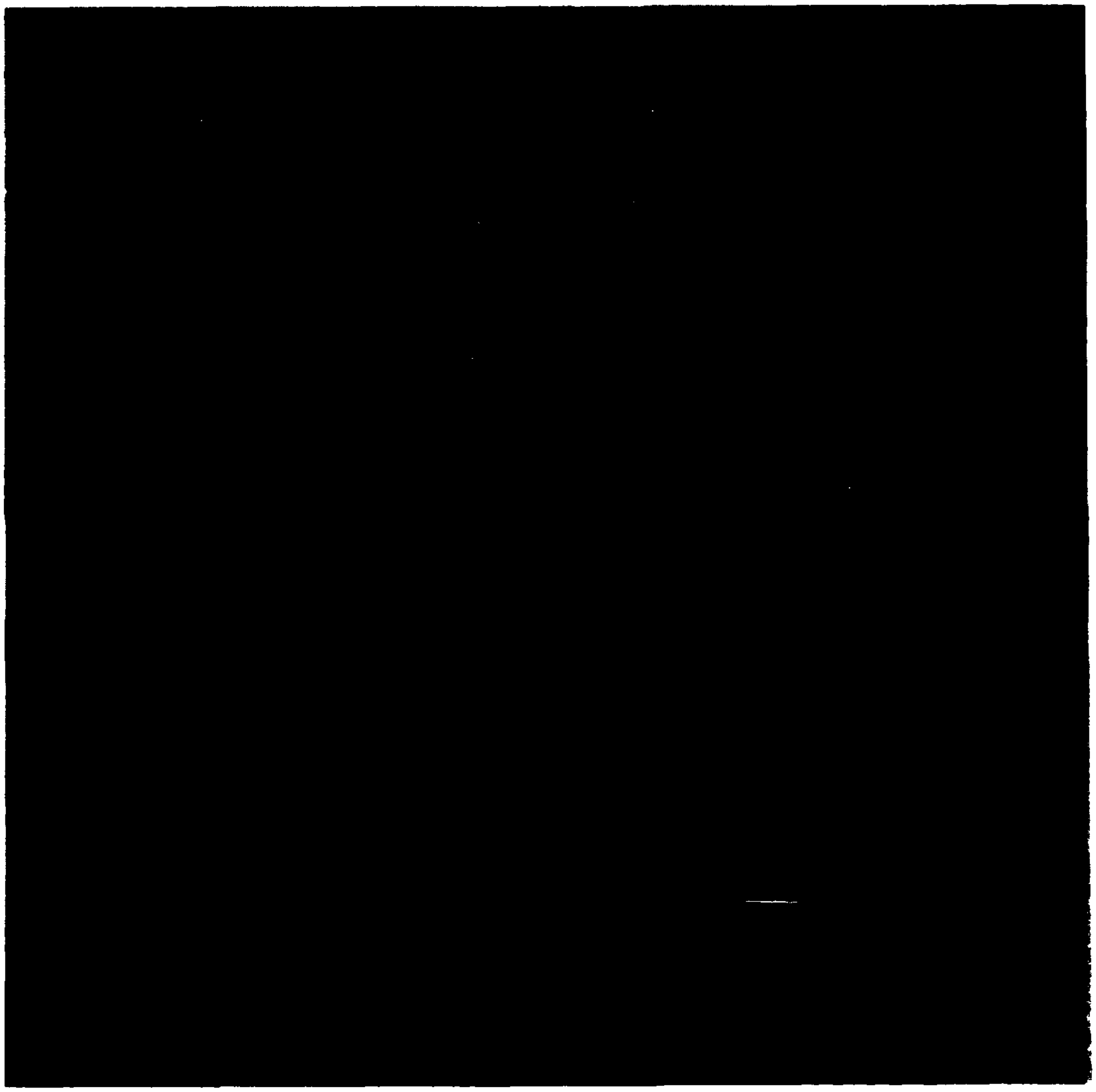
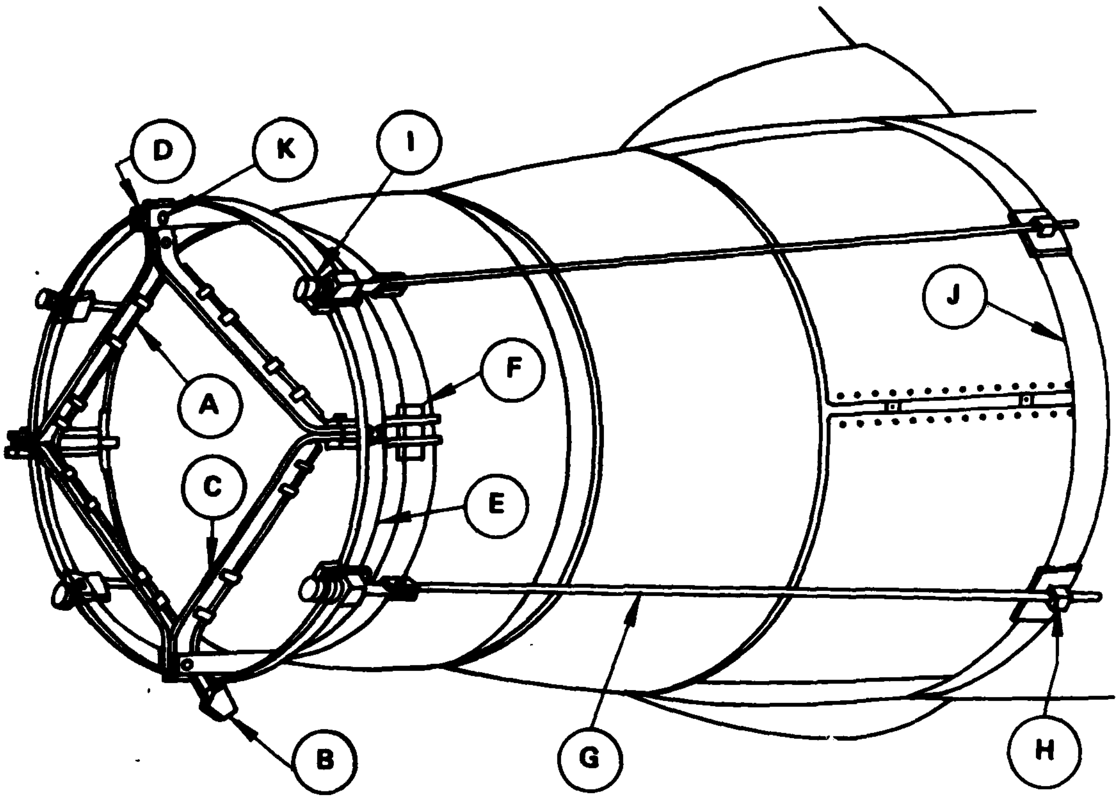


Figure 11 Federal Aviation Administration Exhaust Sampling Rake Prior to Installation on Engine (76-441-4072-A)



LEGEND:

A. PROBE TUBE
B. PROBE OUTLET MANIFOLD
C. PROBE BACK-UP STRUCTURE
D. PROBE MOUNT CLEVIS
E. TORSIONAL SUPPORT RING
F. CLEVIS MOUNT PAD
G. TENSIONING ROD
H. TENSIONING ROD ADJUSTING NUT
I. THERMAL EXPANSION SPRING
J. REVERSER FORWARD SHROUD
K. PROBE ATTACH BOLTS

Figure 12 Typical Engine Installation of Federal Aviation Administration Sampling Rake

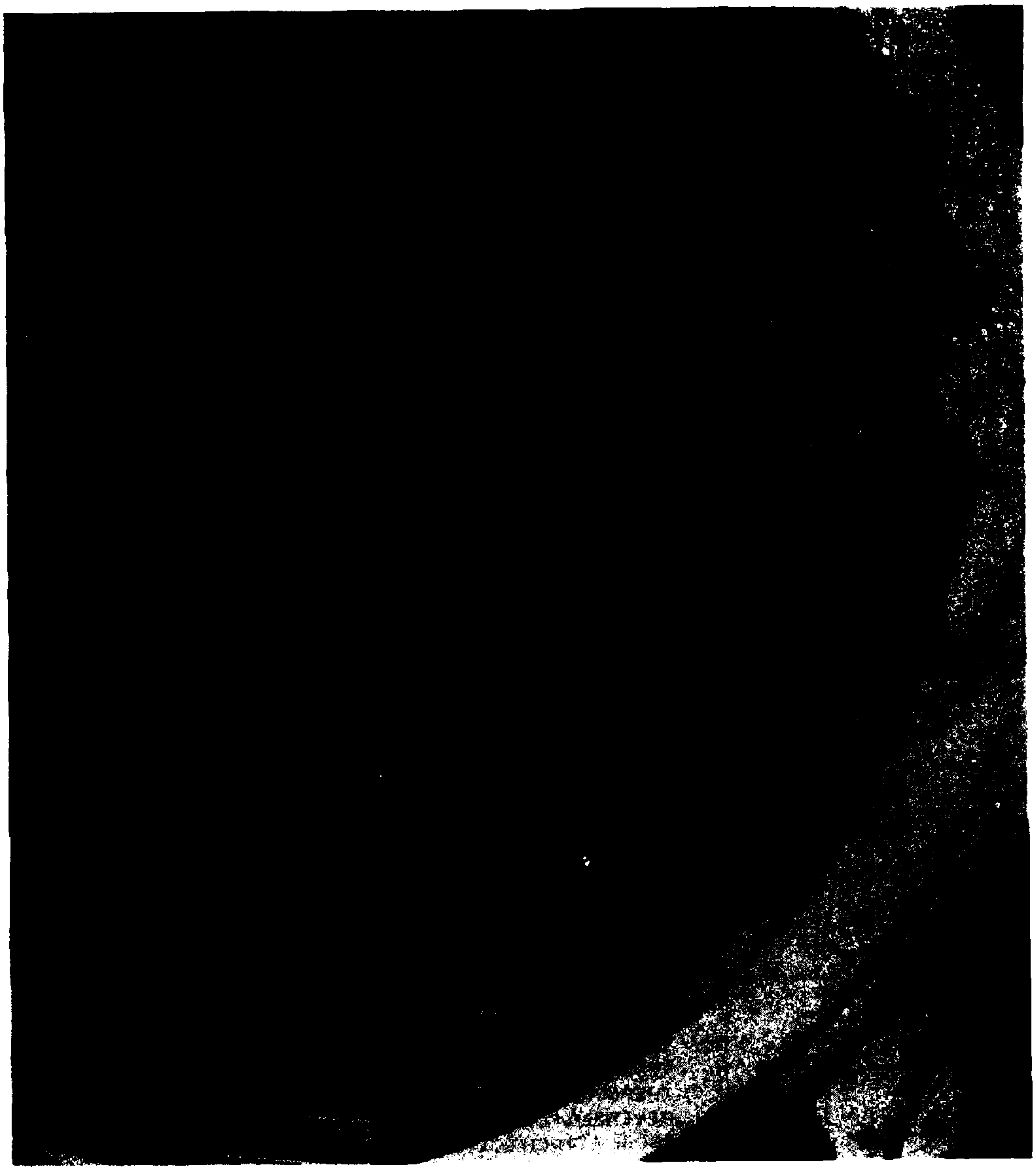


Figure 13 Federal Aviation Administration Exhaust Sampling Rake Mounted on X-686 Experimental Engine *76-441-4072-D*

D. TEST CONDITIONS AND PROCEDURES

The Federal Aviation Administration sponsored engine tests were conducted in a manner simular to that of other JT9D experimental engines at Pratt & Whitney Aircraft. Test stand inlet conditions are not artifically controlled so that the engines are run during various ambient temperature and barometric conditions and rarely on a "standard" day. Engine performance parameters are normally corrected to standard day conditions (Appendix A). Since the nature of this program was oriented to measurement of emissions at specific power levels, the steady state emissions data were taken for most points by establishing combustor inlet temperature level, regardless of ambient conditions. The Standard Day JT9D-7A Gas Generator Reference Conditions are tabulated in Table I for the four EPA-specified sea level static power settings. The emission data were corrected from the observed combustor inlet conditions to the corresponding standard day reference conditions for presentation in this report.

TABLE I

STANDARD DAY JT9D-7A GAS GENERATOR REFERENCE CONDITIONS

Engine Model	EPA Power Level	Thrust N	Thrust lbf	Inlet Fuel Flow kg/hr	Inlet Fuel Flow lbm/hr	Combustor Inlet Temperature K	Combustor Inlet Temperature ^oF	Combustor Inlet Pressure N/m^2	Combustor Inlet Pressure psia	Combustor Fuel-Air Ratio
JT9D-7A	Idle	14,234	3,200	780	1,720	447	345	3.69×10^5	53	0.0105
	Approach	61,585	13,845	2,109	4,650	588	598	8.91×10^5	129	0.0134
	Climb	174,494	39,228	6,010	13,250	736	864	19.38×10^5	281	0.0206
	Takeoff	205, 284	46,150	7,303	16,100	764	916	21.68×10^5	323	0.0229

Table II presents two successive programs formulated to evaluate the Federal Aviation Administration rake sampling ability relative to the cruciform rake and the Station 7 rake which was used to accumulate most of the emission data during the Phase III Experimental Clean Combustor Program. After approximately a five minute stabilization period at each test point, a set of engine performance data, combustor section pressure, and exhaust gas emission data were simultaneously recorded. Smoke samples were only taken at higher power settings as indicated.

TABLE II

ENGINE TEST PROGRAM

Engine Run Point	Emissions Rake (CO, THC, & NO_x) 24 Pt	FAA	ST.7	Engine Condition	Temperature – T_4 (°K)	(°F)	Percent Pilot Fuel	Smoke 24 Pt	FAA
1	X		X	*SLTO	748	887	28	X	
2	X		X	Climb	718	832	34	X	
3	X		X	Sub Climb	665	737	36		
4	X		X	Approach	576	577	50		
5	X		X	High Idle	483	409	100		
6	X		X	Idle	439	331	100		
	Removed 24 Pt Rake and Installed FAA Rake								
7		X	X	Idle	448	346	100		
8		X	X	Max. Thrust	759	906	27		X
9		X	X	Climb Pilot Fuel Split	741	874	33		
10		X	X	Climb	729	853	34		X
11		X	X	Climb Pilot Fuel Split	744	880	29		X
12		X	X	Climb Pilot Fuel Split	740	872	21		X
13		X	X	Sub Climb	703	805	34		X
14		X	X	High Approach	669	745	36		
15		X	X	Approach Pilot Fuel Split	583	589	51		
16		X	X	Approach Pilot Fuel Split	581	586	41		
17		X	X	Approach Pilot Fuel Split	582	588	61		
18		X	X	Approach Pilot Fuel Split	582	588	84		
19		X	X	Idle	437	327	100		
20		X	X	Idle	451	352	100		
21		X	X	Idle	491	423	100		

*Maximum safe operating conditions

E. DATA ANALYSIS PROCEDURES

1. Emission Data Reduction Procedure

The raw emission data generated at each test condition were transmitted directly to an on-line computer for processing. The voltage response of the gaseous constituent analyzers were converted to an emission concentration, based on the calibration curves of each instrument, and then used to calculate emission indices, carbon balance fuel/air ratio, and combustion efficiency. The emission index and carbon balance fuel/air ratio calculations were performed in accordance with the procedures established in SAE ARP 1256 [Reference 2].

In order to compare combustor development engine emission data between runs, it is necessary to correct emission data to the standard conditions listed in Table I. The basis for setting most test points was combustor inlet temperature (T_{t4}). All adjustment of observed emission data were made relative to the observed value of combustor inlet temperature, thereby obviating the need to make an inlet temperature correction. Curves of combustor inlet pressure, fuel/air ratio, and combustor reference velocity versus inlet temperature were generated for the reference JT9D-7A engine operating at standard day ambient conditions.

Comparison of observed and reference combustor operating conditions for the steady-state tests in experimental engine X-686 revealed that only inlet pressure deviated significantly from the reference engine characteristics. Deviations up to 10 percent were recorded at high power engine conditions. Deviations were less than 12 percent at low power conditions. The observed combustor reference velocity was essentially identical to the standard engine characteristic, and the fuel/air ratio was only slightly (0-3 percent) higher than the standard engine. In view of the relative imprecision of currently available fuel/air ratio correction factors and the demonstrated dependence on combustor configuration, it was decided not to attempt a fuel/air corrections. In addition, the NO_x data were corrected to a standard inlet air humidity of 6.3 g H_2O/kg dry air. The data adjustment equations for the gaseous emission species are as follows:

$$(1)\quad NO_x\text{ corr.} = NO_x\text{ meas.}\left(\frac{P_{t4}\text{ std.}}{P_{t4}\text{ meas.}}\right)^{0.5} e^{0.0188\,(H\text{ meas.} - 6.3)}$$

$$(2)\quad CO\text{ corr.} = CO\text{ meas.}\,\frac{(P_{t4}\text{ meas.})}{(P_{t4}\text{ std.})}$$

$$(3)\quad THC\text{ corr.} = THC\text{ meas.}\,\frac{(P_{t4}\text{ meas.})}{(P_{t4}\text{ std.})}$$

where:

NO_x = Emission index of oxides of nitrogen (g/kg fuel)
CO = Emission index of carbon monoxide (g/kg fuel)
THC = Emission index of total hydrocarbons (g/kg fuel)

P_{t4} = Combustor inlet total pressure
H = Inlet specific humidity (g H_2O/kg air)

and subscripts:

corr. = Relates to value at corrected or standard condition
meas. = Relates to value at measured condition

Exhaust smoke data are presented on an as-recorded basis, due to the lack of suitable extrapolation information. As was indicated above, the only significant deviation when presented on an inlet temperature basis is in combustor inlet pressure. An increase in pressure to the correct standard engine level would be expected to increase exhaust smoke.

2. EPA Parameter Calculation

The U. S. Environmental Protection Agency emission standards for aircraft engines are expressed in terms of an integrated EPA parameter (EPAP). This parameter combines emission rates at the engine idle, approach, climb, and takeoff operating modes, integrated over a specified landing, takeoff cycle [Reference 3]. The equation for this calculation is as follows:

$$(4)\quad EPAP_i = \frac{\Sigma j \; \frac{t_j}{60} \; W_{Fj} \, EL_{ij}}{\Sigma j \; \frac{t_j}{60} \; F_{Nj}} \text{ (lbm pollutant/1000 lbf thrust-hr/LTO cycle)}$$

where:

EI = emission index (lbm pollutant/1000 lbm fuel)
t = time at engine mode (min)
F_N = net thrust (lbf)
W_F = fuel flow rate (lbm/hr)

and subscripts:

i = emission category (CO, THC, NO_x)
j = engine mode (idle, approach, climb, SLTO)

The engine data used to calculate the EPAP, presented in Table III, were obtained from the latest JT9D-7A performance table.

TABLE III

JT9D-7A ENGINE DATA FOR EPAP CALCULATION

Engine Mode	Time (t) min.	Net Thrust (F_n) lbf	Fuel Flow (W_f) lbm/hr
Idle	26.0	3200	1720
Approach	4.0	13845	4650
Climb	2.2	39228	13250
SLTO	0.7	46150	16100

Substituting the engine data from Table IV equation (4) becomes:

$$(5)\quad EPAP_i = 0.174 EI_{Idle} + 0.072\, EI_{approach} + 0.114\, EI_{climb} + 0.0441\, EI_{SLTO}$$

The emission indices used in equation (5) are obtained from plots versus inlet temperature at the JT9D-7A four values of combustor inlet temperature corresponding to the EPA power points (Table I).

3. Combustor Performance Calculation Procedure

Measured and calculated combustor performance parameters are listed in Table IV.

TABLE IV

SUMMARY OF REPORTED COMBUSTOR PERFORMANCE PARAMETERS

Parameter	Symbol	Units	Measured	Calculated
Total Airflow	W_{a4}	kg/s	X	
Total Combustor Airflow	W_{ab}	kg/s		X
Pilot Fuel Flow	W_f pilot	kg/s	X	
Main Fuel Flow	W_f main	kg/s	X	
Inlet Total Temperature	T_{t4}	K	X	
Inlet Total Pressure	P_{t4}	atm	X	
Reference Velocity	V_{ref}	m/s		X
Pattern Factor	PF	--		X
Inlet Air Humidity	H	gH_2O/kg air	X	
Fuel/Air Ratio	f/a			X
Pressure Loss	$\Delta P_t/P_t$			X
Combustion Efficiency	η_c	%		X

Definitions of those calculated parameters which require further clarification are presented below.

a. Total Combustor Airflow

The total combustor airflow is determined by subtracting the turbine cooling air and other fixed bleed flows from the measured engine air flow.

b. Reference Velocity

The reference velocity (V_{ref}) is defined as that flow velocity that would result if the total combustor airflow, at the compressor discharge temperature and static pressure, were passed through the combustor liner at the maximum cross sectional area. This area is $0.218 m^2$ for the Vorbix combustor tested in this program.

c. Fuel/Air Ratio

Both measured and carbon derived fuel/air ratios (f/a) have been calculated and recorded for all test points run in this program. The measured, or performance fuel/air ratio, is the ratio of total fuel flow to total combustor airflow. The pilot and main fuel/air ratios are defined by multiplying the overall fuel/air ratio by the fractional pilot and main fuel split, respectively. The carbon balance derived fuel/air ratio is determined by using gas sample data to determine the carbon balance of the exhaust gases.

d. Total Pressure Loss

The total pressure loss ($\Delta P_t/P_t$) is calculated from the following equation:

$$(6) \qquad \frac{\Delta P_t}{P_t} = \frac{P_{t5} - P_{t4}}{P_{t4}}$$

where:

P_{t5} = Average combustor exit total pressure
P_{t4} = Average compressor discharge total pressure

e. Combustion Efficiency

The combustion efficiency (η_c) is calculated on a deficit basis using the measured concentrations of carbon monoxide and total unburned hydrocarbons from the gas sample data. The calculation is based on the assumption that the total concentration of unburned hydrocarbons could be assigned the heating value of methane (CH_4). The equation is:

$$(7) \qquad \eta_c = 100 - 100 \left(\frac{4343X + 21500Y}{18.4\,(10)^6} \right)$$

where:

X = measured carbon monoxide concentration in g/kg fuel

Y = measured total unburned hydrocarbon concentration in gCH_4/kg fuel.

CHAPTER III

RESULTS AND DISCUSSION

A. INTRODUCTION

The following sections discuss the emission and performance results obtained in comparative engine testing of the Federal Aviation Administration (FAA), National Aeronautics and Space Administration/Pratt & Whitney Aircraft (NASA/P&WA) exhaust emission rakes and the Station 7 instrumentation.

The data in this chapter has been confined to that which substantiates the major accomplishments of the program. A compilation of the detailed data obtained during the program is presented in Appendix B.

B. EMISSION RESULTS

Section B1 presents a comparison of the emission indices obtained with the FAA and the 24-point exhaust rakes. Section B2 presents the EPA parameters and the smoke results.

1. Comparison of Emissions

The comparisons were made by plotting the corrected emissions data obtained with the FAA and 24-point exhaust rakes against the corresponding corrected emission values obtained with the Station 7 probes.

Excellent agreement was obtained for oxides of nitrogen with deviations of less than 5 percent, as shown in Figure 14. However, the FAA rake consistently sampled carbon monoxide emission levels that were slightly higher than the 24-point rake values, as shown in Figure 15. The total unburned hydrocarbon emission data comparison, contained in Figure 16, appears to indicate a large amount of data scatter among the various probes. However, this scatter results in part from inaccuracies associated with measurement of the very small concentrations of unburned hydrocarbons produced by the Vorbix combustor.

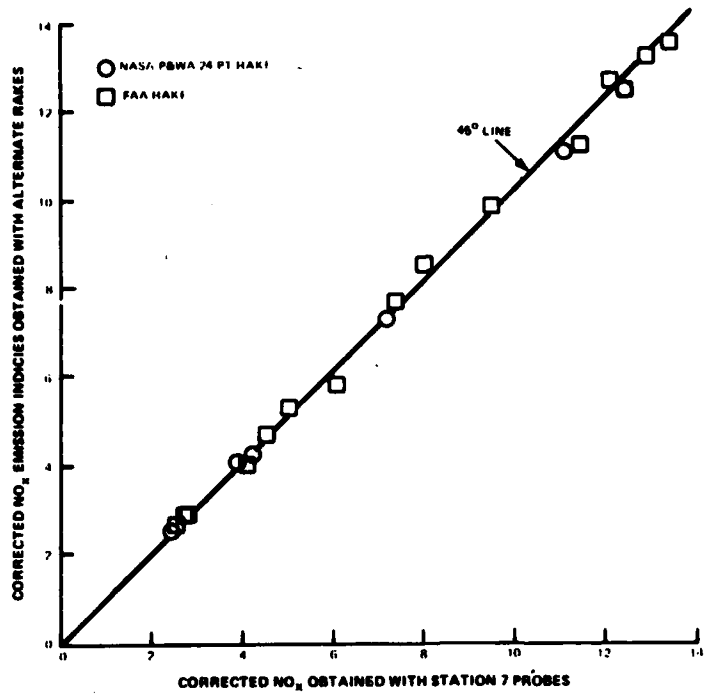


Figure 14 *Relative Indications of Gas Sampling Rakes for Oxides of Nitrogen Emissions*

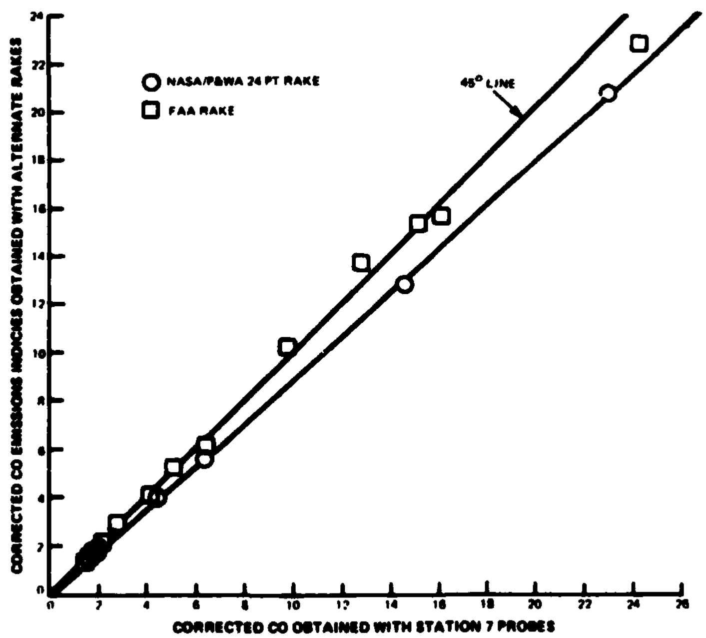


Figure 15 *Relative Indications of Gas Sampling Rakes for Carbon Monoxide Emissions*

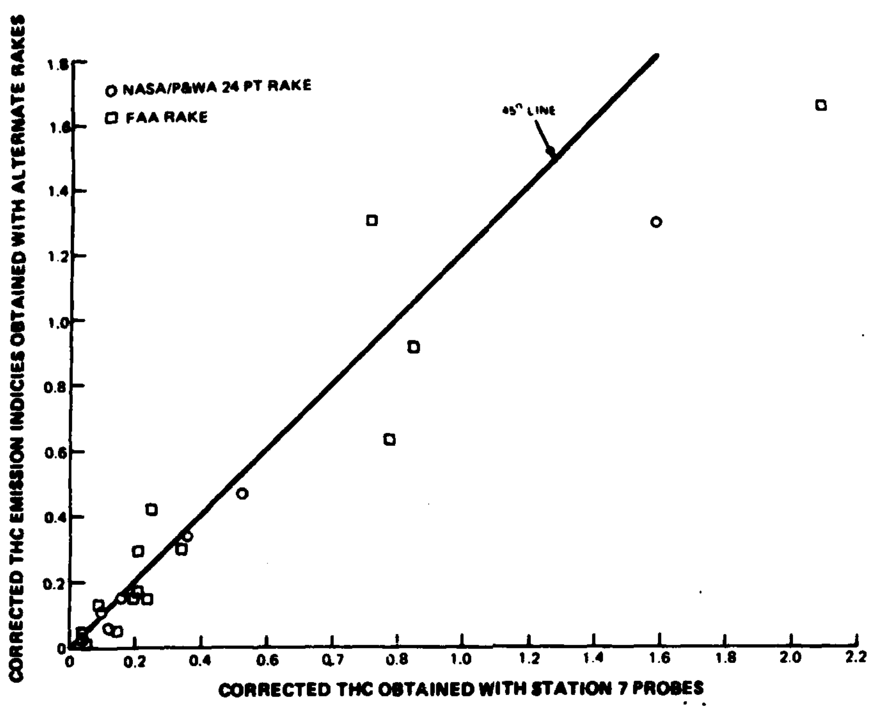


Figure 16 Relative Indications of Gas Sampling Rakes for Total Unburned Hydrocarbon Emissions

Smoke measurements, although few, produced nearly identical values with the FAA and the 24-point rakes. These data are in agreement with values obtained in the Experimental Clean Combustor Program where a maximum of 30 was recorded.

The conventional measure of gas sample validity is the comparison of the metered fuel/air ratio based on direct measurement of engine fuel flow and core airflow with the calculated fuel/air ratio based on carbon balance of the exhaust gas specie concentration detected by the sampling probe. Data for the comparison is presented in Figure 17. The FAA rake produced carbon balance fuel/air ratios that were approximately 11 percent higher than the metered fuel/air ratios at the idle and approach conditions. All other fuel/air ratios exceeded the metered values by approximately 5 percent which is consistent with the results obtained during the Experimental Clean Combustor Program.

This difference between high and low power results did not exist with the 24-point sampling rake. This suggests that sampling from a nearly single radial position, as is done with the FAA rake, produces an average exhaust sample that is sensitive to exhaust emission radial profile. Although selective radial sampling to define the radial exhaust emission profile was not conducted during this program, the severity of the change in profile between high and low power can be seen from the combustor exit radial temperature profiles presented in Figure 18. These profiles were obtained during Phase III of the Experimental Clean Combustor Program [Ref. 1], and show that single-stage pilot only operation at idle produces a temperature profile peaked toward the ID. This behavior may also explain the higher carbon monoxide emissions obtained with the FAA rake at idle and approach power.

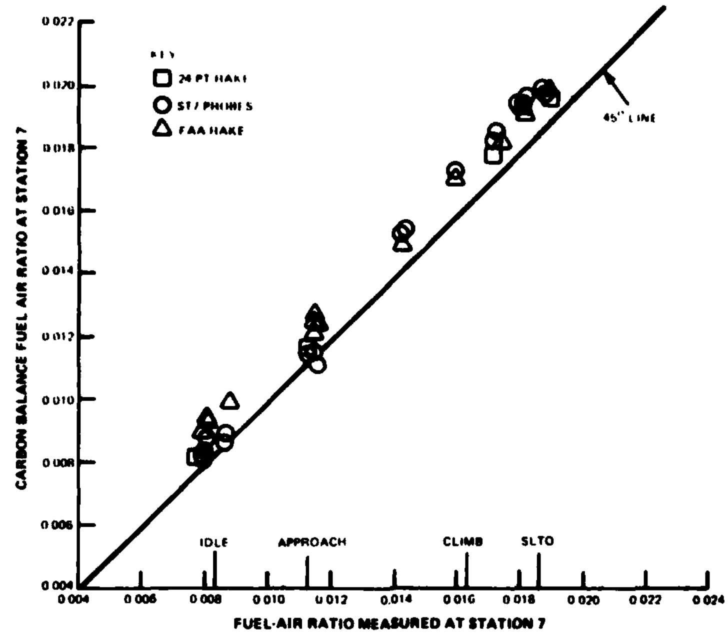


Figure 17 *Comparison of Fuel/Air Ratios Determined By Carbon Balance Method From Various Gas Sampling Probes and By Direct Measurement of Fuel Flow and Airflow*

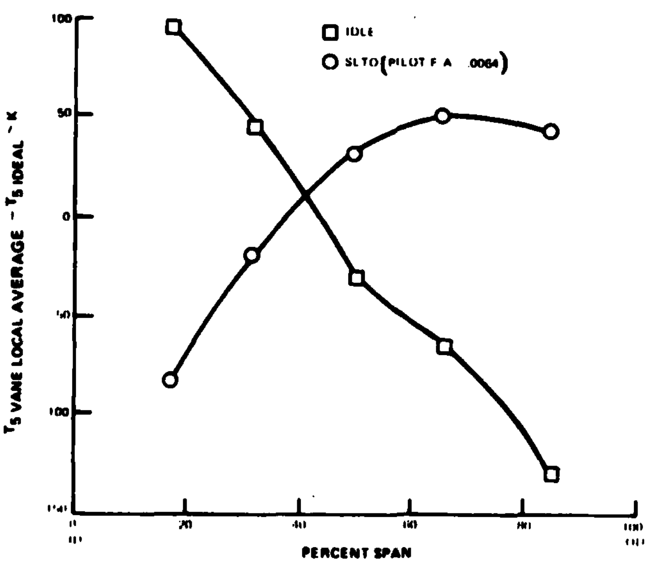


Figure 18 *Exit Radial Temperature Profile for the Vorbix Combustor at Idle and Sea Level Takeoff Conditions*

The EPA parameters were calculated for the Vorbix combustor from data obtained from Station 7, FAA and 24-point sampling rakes. The initial step in determining EPA parameters was to establish emission indices versus combustor inlet temperature curves presented in Figures 19, 20 and 21. Using these curves emission indices at the four EPA power settings were determined.

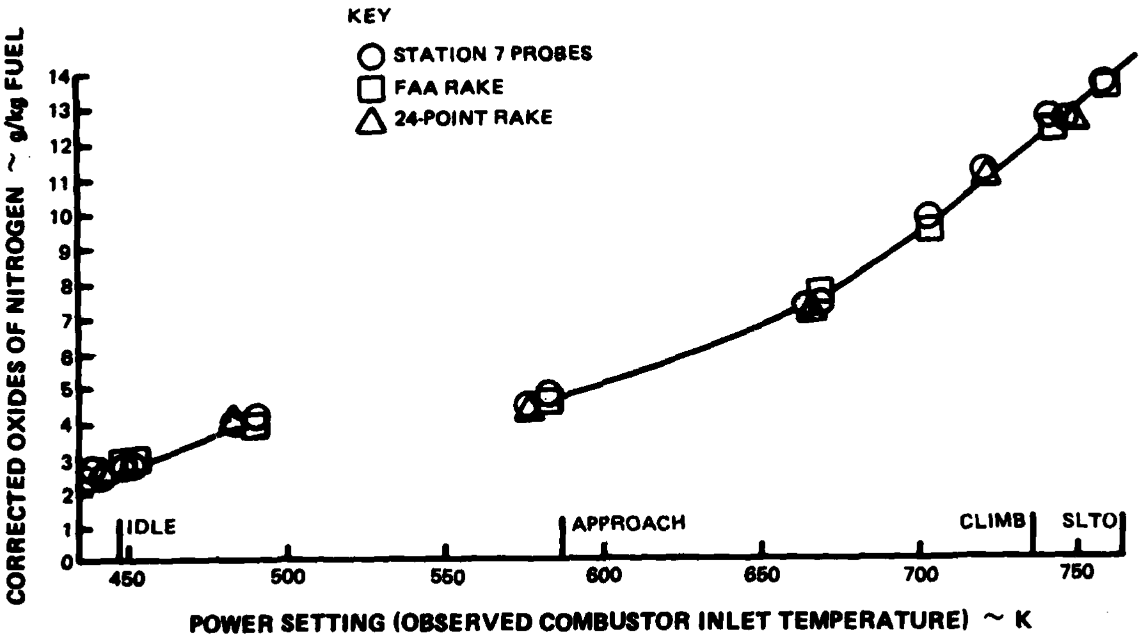


Figure 19 Corrected Oxides of Nitrogen Emissions for the Vorbix Combustor Obtained With Different Sampling Systems

The EPA parameters computed in this manner and SAE smoke numbers for the three rakes are presented in Table V. As shown, good agreement was obtained for oxides of nitrogen and total unburned hydrocarbon EPA parameters as well as SAE smoke numbers. The carbon monoxide EPA parameter calculated from the FAA rake and Station 7 probes emission indices were approximately 10 percent higher than the 24-point rake values as a result of the higher idle carbon monoxide emissions.

Similar results were obtained in comparative emission rake testing during the Experimental Clean Combustor Program. In addition to obtaining emissions with the 24-point rake and Station 7 probes, the program included traversing the 24-point rake in 5 degree increments over a 45 degree interval. The Station 7 probes produced CO emissions that were approximately 11 percent higher than the 24-point rake.

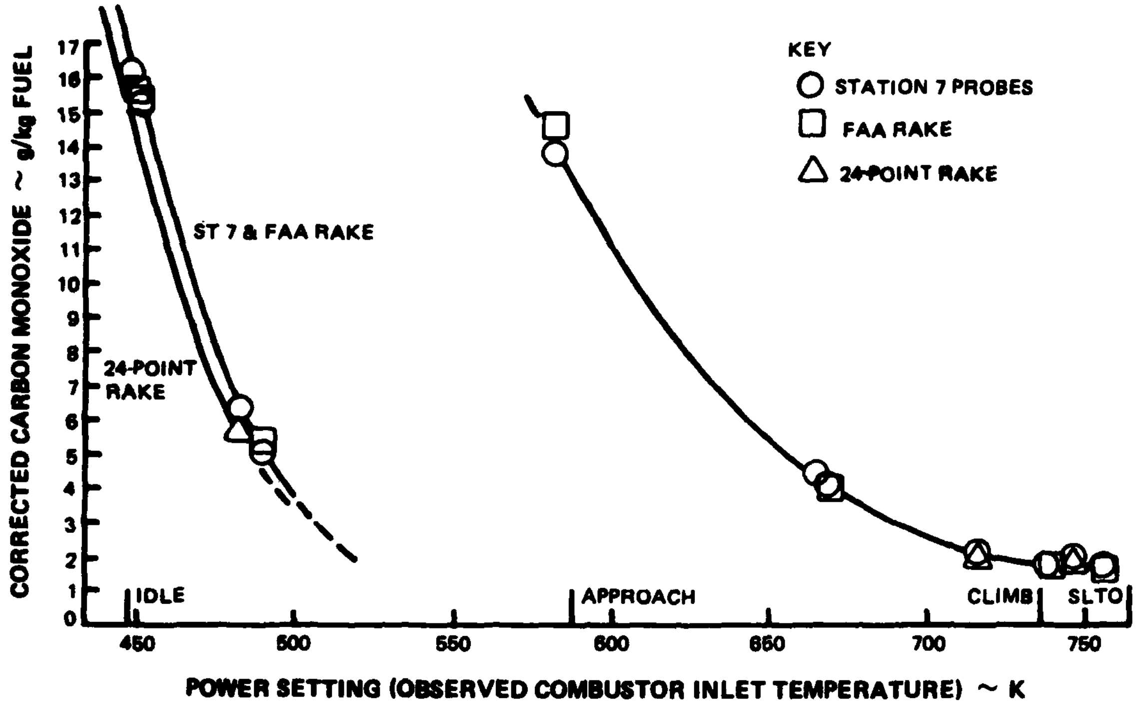


Figure 20 *Corrected Carbon Monoxide Emissions for the Vorbix Combustor Obtained With Different Sampling Systems*

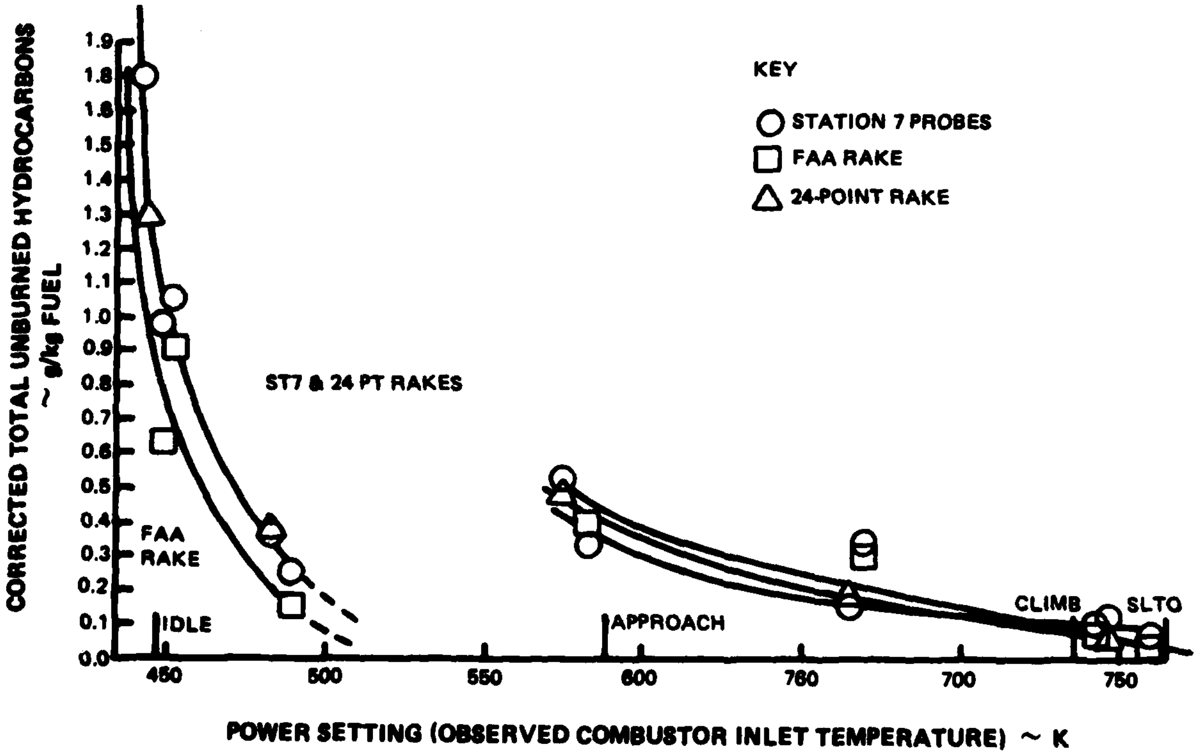


Figure 21 *Corrected Total Unburned Hydrocarbon Emissions for the Vorbix Combustor Obtained With Different Sampling Systems*

TABLE V

ENVIRONMENTAL PROTECTION AGENCY PARAMETERS
AND SMOKE RESULTS

	Oxides of Nitrogen	Carbon Monoxide	Total Unburned Hydrocarbons	Smoke Number
NASA/P&WA 24-Point Rake	2.7	3.6	0.2	31
FAA Rake	2.8	4.0	0.2	29
Station 7 Rake	2.8	4.0	0.2	Not Available

Note: All emissions data are corrected to standard JT9D-7A engine condition and inlet humidity of 6.3 gH_2O/kg dry air.

C. ENGINE PERFORMANCE

A review of the effects of the ECCP and FAA emissions rakes on engine performance indicates that the FAA rake resulted in a 1.3% reduction in effective primary area at 1.42 EPR (P_{t7}/P_{t2}). This engine performance penalty caused by tailpipe blockage is best illustrated by Figure 22, a plot of P_{s4}/P_{t7} (expansion thru the turbine) vs. EPR (P_{t7}/P_{t2}). This plot indicates that the ECCP rake has no measurable effect on engine match even though it has more physical blockage area than the FAA rake. This is due to the proximity of the FAA rake (7.6 cm. from tailpipe exit plane versus 35.6 cm. for the ECCP rake).

The 1.3 percent reduction in effective primary area had negligible effect on setting engine conditions and did not impact emission measurements.

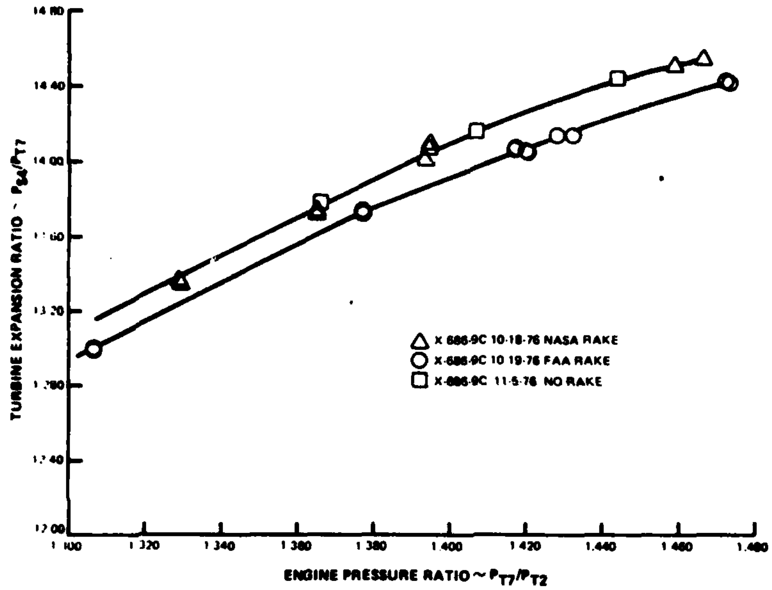


Figure 22 Affect of Sampling Rake on Engine Performance

CONCLUDING REMARKS

Based on the results of two engine emissions tests conducted with two different sampling rakes, the principal conclusions derived from this work are:

1. The CO, THC, NO_x and smoke data obtained from the FAA diamond and NASA/PWA rakes agree well at high power.

2. At low power levels (idle and approach) the CO emissions measured by the FAA rake, and Station 7 probes were approximately 10 percent higher than that measured by the NASA/PWA rake.

3. The FAA rakedesign evaluated in this program causes measurable tailpipe blockage and consequent engine performance shifts.

   The performance shifts had negligible affect on setting engine conditions and did not impact emission measurements.

APPENDIX A

EQUIPMENT AND EXPERIMENTAL PROCEDURES

1. EXPERIMENTAL ENGINE PERFORMANCE INSTRUMENTATION

A. PARAMETERS MEASURED

Table A-1 list the engine parameters measured and indicated measurement accuracy using fixed engine and test stand instrumentation.

TABLE A-1

PARAMETERS MEASURED

Parameter	Measurement Accuracy
T_{T2} - Engine Inlet Temperature	± 0.56K (1°F)
Gearbox Breather Pressure	± 34.47 N/m^2 (0.005 psi)
Gearbox Breather Temperature	± 1.1K (2°F)
N_1 - Low Rotor Speed	± 0.1%
N_2 - High Rotor Speed	± 0.1%
F_N - Engine Thrust	± 0.5% above 111,200 N (25,000 lb)
	± 1.5% below 111,200 N (25,000 lb)
P_{T2} - Engine Inlet Total Pressure	± 137.90 N/m^2 (0.02 psi)
$P_{T2.5}$ - Fan Discharge Total Pressure	± 344.74 N/m^2 (0.05 psi)
P_{T7} - Engine Exit Total Pressure	± 137.90 N/m^2 (0.02 psi)
T_{T6} - High Turbine Discharge Temperature	± 3.89K (7°F)
T_{T7} - Engine Exit Total Temperature	± 2.78K (5°F)
P_{S4} - Burner Pressure	± 10342.13 N/m^2 (1.5 psi)
W_f - Total Engine Fuel Flow	± 0.75%

These data are used to compute overall engine performance characteristics. The pilot and main fuel flows and a redundant measurement of total fuel flow are obtained from the bread-board electronic fuel control instrumentation. Redundant measurement of other selected engine parameters was also possible using the fuel control instrumentation.

B. ENGINE PERFORMANCE DATA CORRECTION

The observed engine performance data are corrected as follows:

- Corrected Observed Thrust

$$\frac{F_{N\ OBS}}{\delta_{t2}} = \frac{\text{Observed Thrust}}{\delta_{t2}}$$

- Corrected Net Thrust

$$\frac{F_N}{\delta_{t2}} = \frac{F_{N\ OBS}}{\delta_{t2}} + \frac{\Delta F_N}{\delta_{t2}}\ \text{corr}$$

$$\text{: where} \quad \delta_{t2} = \frac{\text{Observed inlet pressure}}{\text{Standard day inlet pressure}}$$

$$\frac{\Delta F_N}{\delta_{t2}} = \text{Correction from Figure A-1}$$

- Corrected Fuel Flow

$$W_{f\ corr} = \frac{W_f \text{ observed}}{\delta_{t2} + K_C \text{ (temperature correction) x } K_n \text{ (humity correction)}}$$

- Corrected Thrust Specific Fuel Consumption

$$TSFC_{corrected} = \frac{\text{Corrected Fuel Flow}}{\text{Corrected Net Thrust}}$$

- Corrected Rotor Speed

$$N_{corrected} = \frac{\text{Observed Rotor Speed}}{\sqrt{\theta_{t2}}}$$

$$\text{where } \theta_{t2} = \frac{\text{Observed inlet temperature}}{\text{Standard day temperature}}$$

C. DIFFUSER/COMBUSTOR INSTRUMENTATION

Pressure and temperature instrumentation installed on the Vorbix combustor liners and diffuser case passages is summarized in Figure A-2. Typical total pressure and temperature probes installed at the compressor discharge plane (Station 4.0) are shown in Figure A-3.

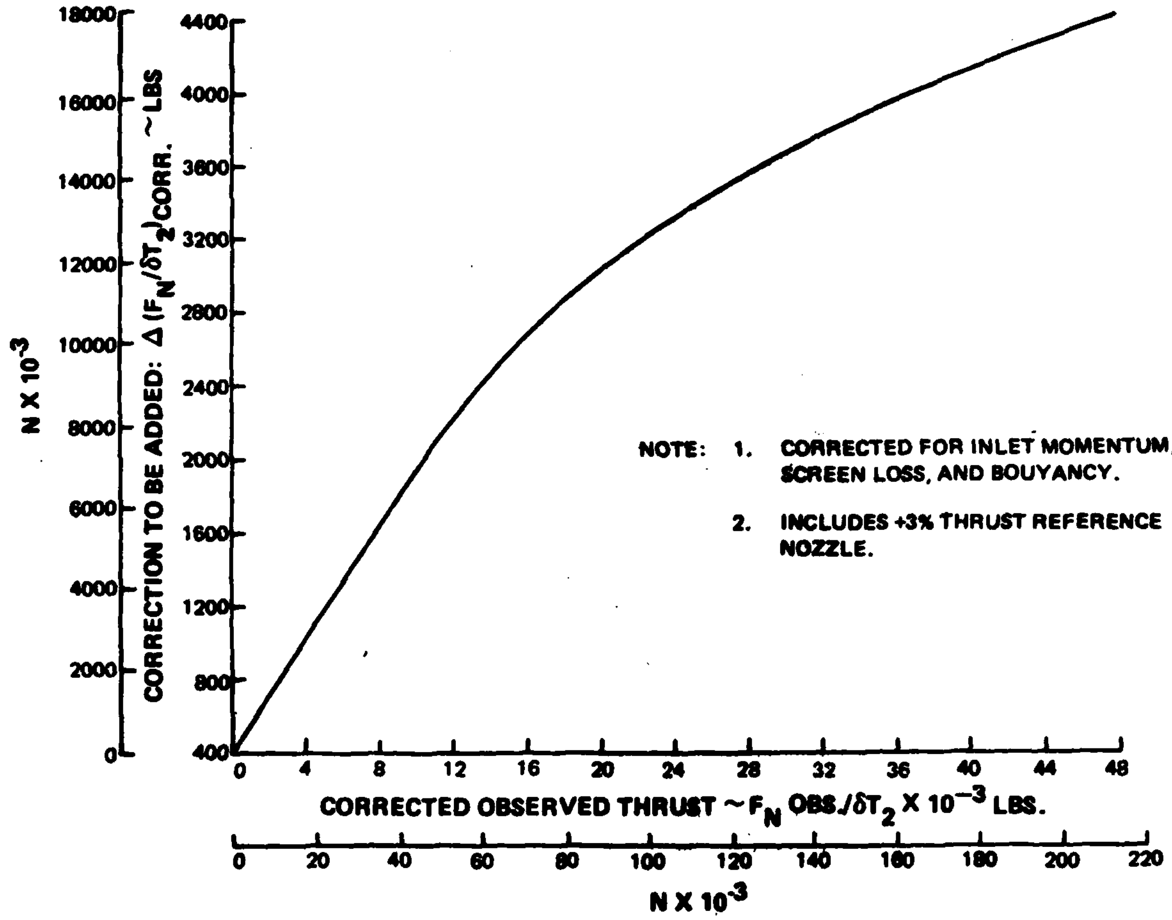


Figure A-1 JT9D Turbofan Engine Test Cell Thrust Correction for Middletown Test Cells

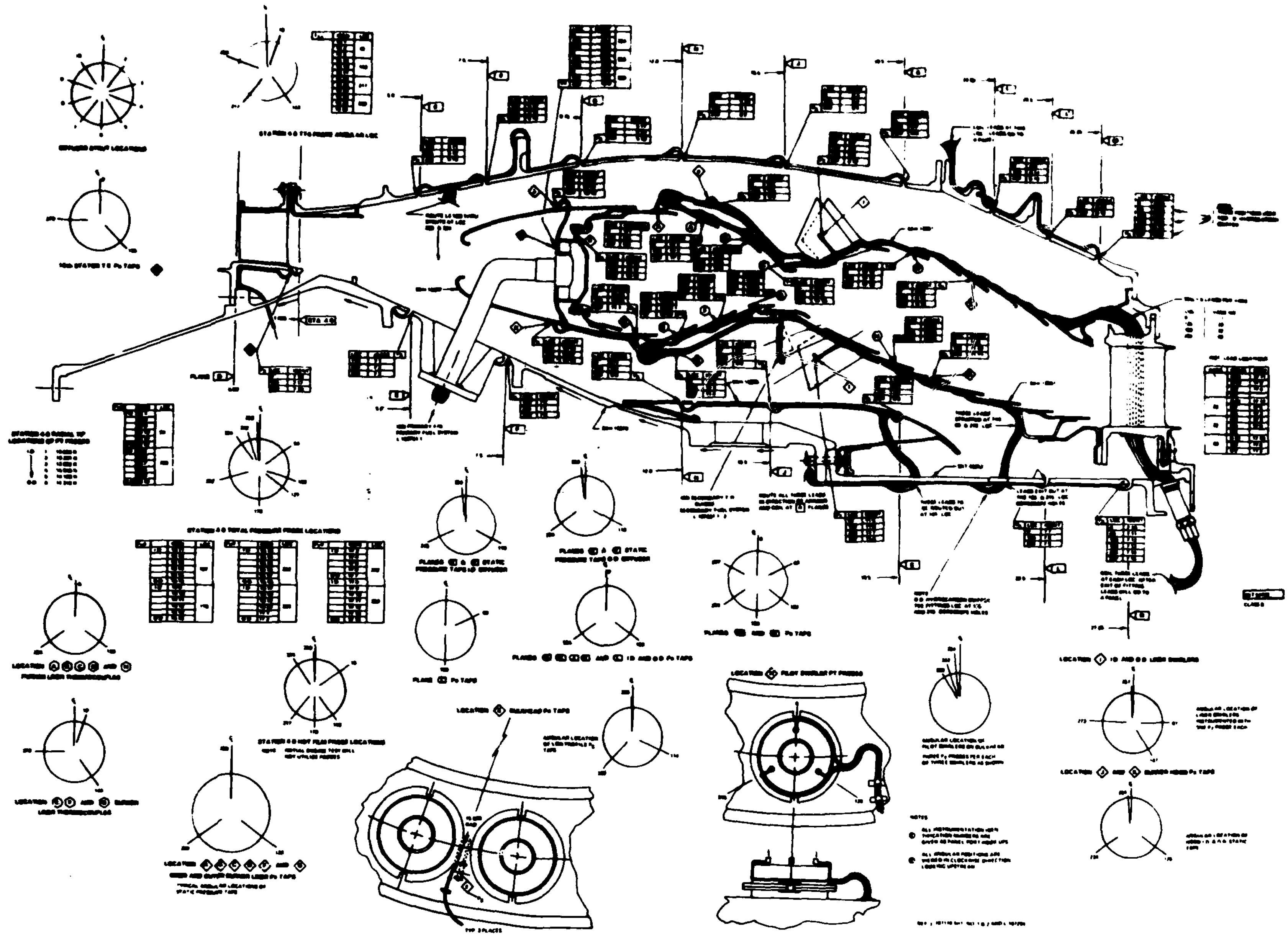


Figure A-2 Vorbix Combustor and Diffuser Case Instrumentation, X-686

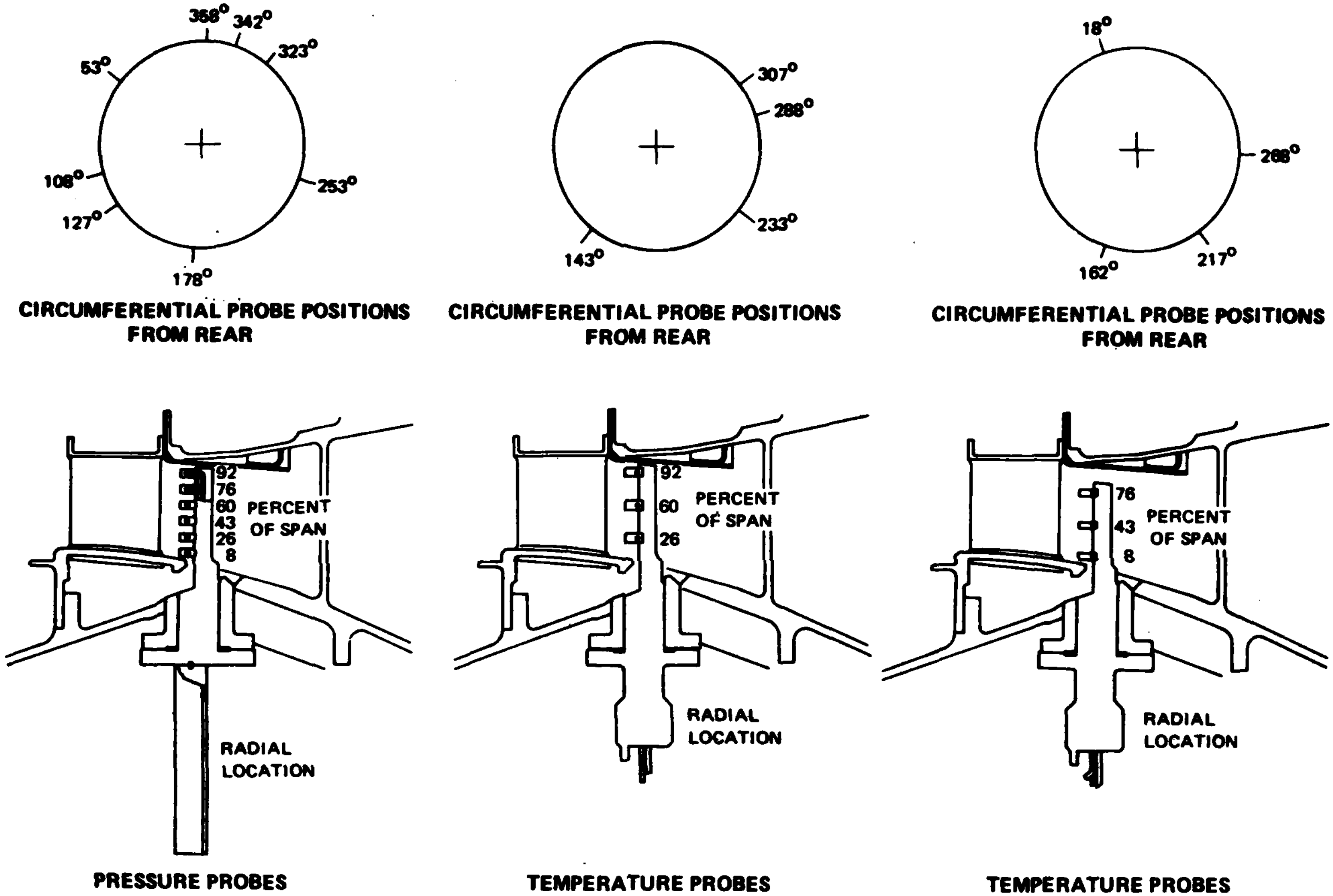


Figure A-3 Station 4 Radial and Circumferential Total Pressure and Total Temperature Probe Locations

2. GAS SAMPLING AND ANALYSIS EQUIPMENT

A. MOBILE GAS ANALYSIS LABORATORY

The Pratt & Whitney Aircraft gas temperature and combustion efficiency (GT&CE) mobile laboratory (Figure A-4) is a specially designed vehicle capable of measuring gaseous combustion exhaust products. Through the use of a telephone link to the centralized Sigma 8 data reduction computer system, measured constituent concentrations can be converted to real time, on-line computations of emission index, combustion efficiency, and combustion exit temperature. The results of these computer calculations, together with the raw data, the measurement uncertainties, and data validity checks are displayed on an interactive scope in the GT&CE mobile laboratory. The GT&CE mobile laboratory is completely self-contained with the exception of the data reduction computer, and incorporates the latest on-line gas analysis instrument for the measurement of carbon dioxide, carbon monoxide, nitrogen, oxygen, hydrogen, oxides of nitrogen, total unburned hydrocarbon, and water vapor. An interior view of the mobile van is shown in Figure A-5. Individual analyzer specifications are summarized in Table A-II.

The GT&CE mobile laboratory utilizes a heated stainless steel metal bellows sample pump to draw a sample of the jet engine combustion products into the sample measurement train. Another larger vacuum-type bypass pump is also incorporated into the sampling system to minimize the residence time of the sample in the sample line. The engine exhaust gas sample is distributed to the various instruments, with each instrument having its own flow metering system. The sample handling system is shown schematically in Figure A-6. The outputs from these instruments are recorded and monitored continuously on strip chart recorders. The analyzer outputs are also digitized and, on command, are sent via a telephone line to a Sigma 8 computer and/or recorded on a cassette-type magnetic tape recording system. The magnetic tape is compatible with the IBM-360 computer which is used for off-line special data reduction and validation programs.

Each instrument is provided with "sample" and "calibration" operating modes. The GT&CE mobile laboratory carries its own calibration, zero and span gases. In support of this mobile laboratory, an in-house analytical laboratory develops calibration gases and maintains standard reference gases which, in most cases, are traceable to the National Bureau of Standards (NBS).

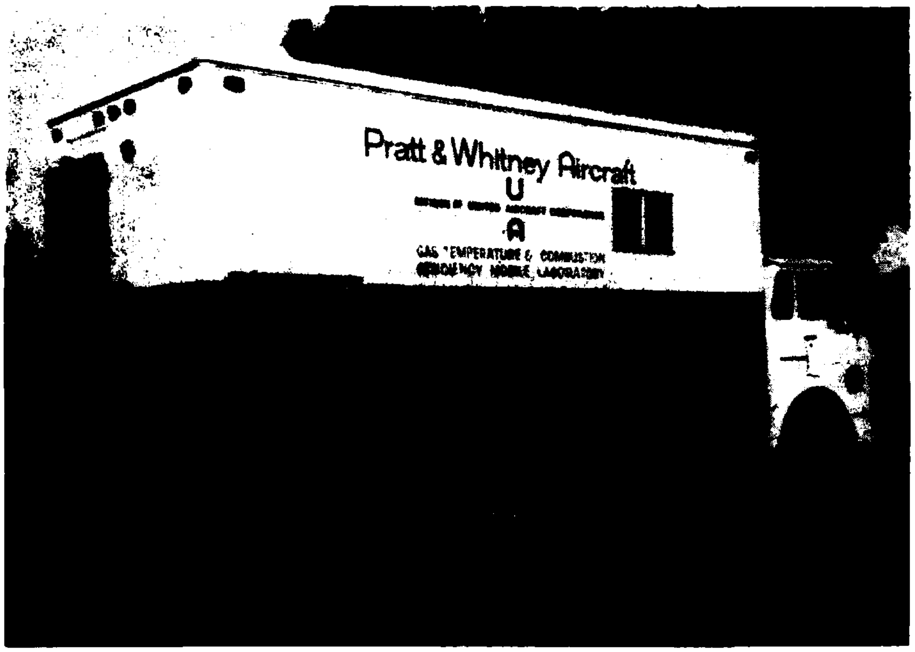


Figure A-4 *Mobile Laboratory for Measurement of Gaseous Combustion Exhaust Products* *(CN-40146)*

Figure A-5 *On-Line Gas Analysis Equipment* *(CN-40168)*

TABLE A-II

ANALYZER SPECIFICATIONS

Component	Range	Direction Method	Minimum Detectability	Error % Full Scale
O_2	0-10% V	Amperometric	0.25% V	± 1.0%
	0-25% V			
N_2	0-90%	Gas Chromatograph	0.1% V	–
H_2	0-1%	Gas Chromatograph	0.1% V	–
	0-5%			
O_2	0-25%	Gas Chromatograph	0.1% V	–
CO	0-100 ppmv	NDIR	2 ppmv	± 2.0%
	0-500 ppmv			± 1.0%
	0-2500 ppmv			± 1.0%
	0-2500 ppmv			± 1.0%
CO_2	0-2% V	NDIR	0.04% V	± 1.0%
	0-5% V		0.25% V	± 1.0%
THC (As Methane)	0-1 ppmv	FID	0.1 ppmv	± 5.0%
	Through 0-50K ppmv			± 1.0%
NO_x	0-2.5, 0-10-6.25, 0-100	CL	0.1 ppmv	± 0.5%
	0-250 - 0 - 1000			
	0-2500			
	0-10000			
H_2O	-45°C - +60°C	CMHY	0.06°C	± 0.4°C

CL - Chemiluminescence
FID - Flame Ionization Detector
NDIR - Non-Dispersive Infrared
CMHY - Chilled Mirror Hygrometer
NDUV - Non-Dispersive Ultraviolet

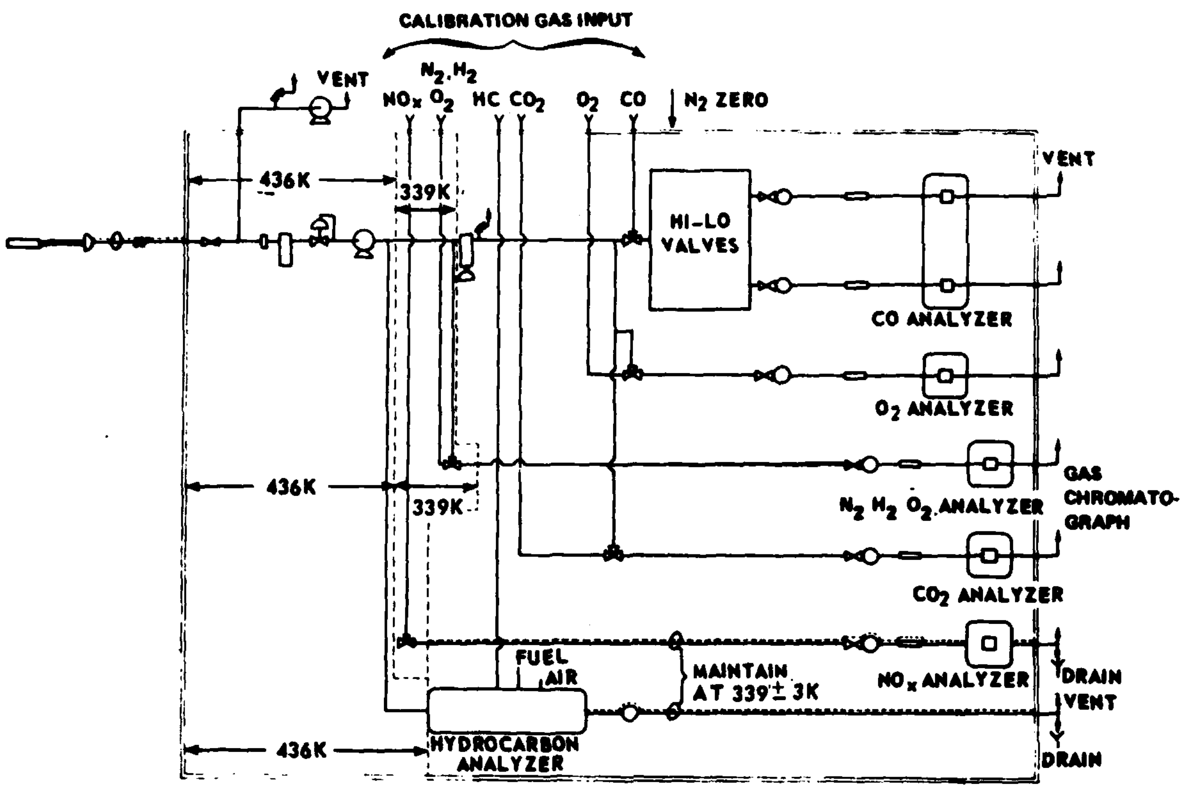


Figure A-6 Exhaust Gas Sample Handling System

B. SMOKE MEASUREMENT CONSOLE

Engine exhaust smoke measurements were obtained using a smoke measuring system that conforms to specifications of the Society of Automotive Engineers Aerospace Recommended Practice 1179 and the Environmental Protection Agency [Reference 1].

The smoke measuring console, shown in Figure A-7, is a semiautomatic electromechanical device which incorporates a number of features to permit the recording of smoke data with precision and relative ease of operation. The smoke console was installed in the engine test cell control room for the duration of the test program. Dimensions of the filter holder and a schematic of the sampling system are shown in Figure A-8. The filter holder has been constructed with a 2.54 cm (1.0 inch) diameter spot size, a diffusion angle θ of 7.25 degrees and a converging angle α of 27.5 degrees.

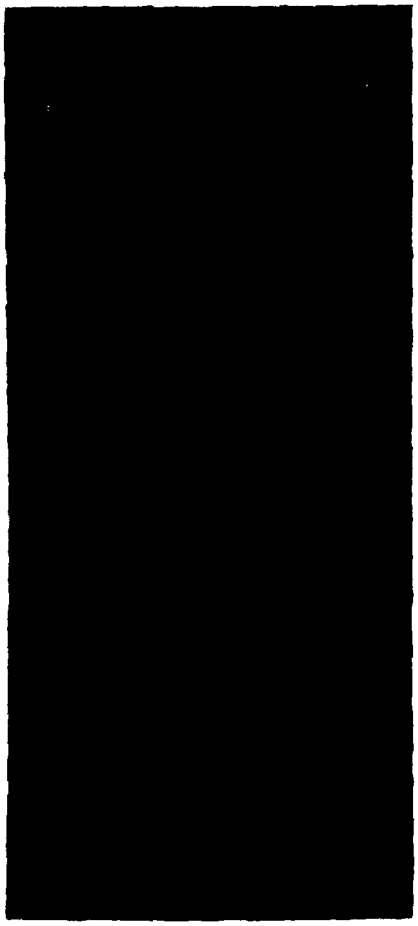


Figure A-7 SAE/EPA Smoke Meter (CN-47639)

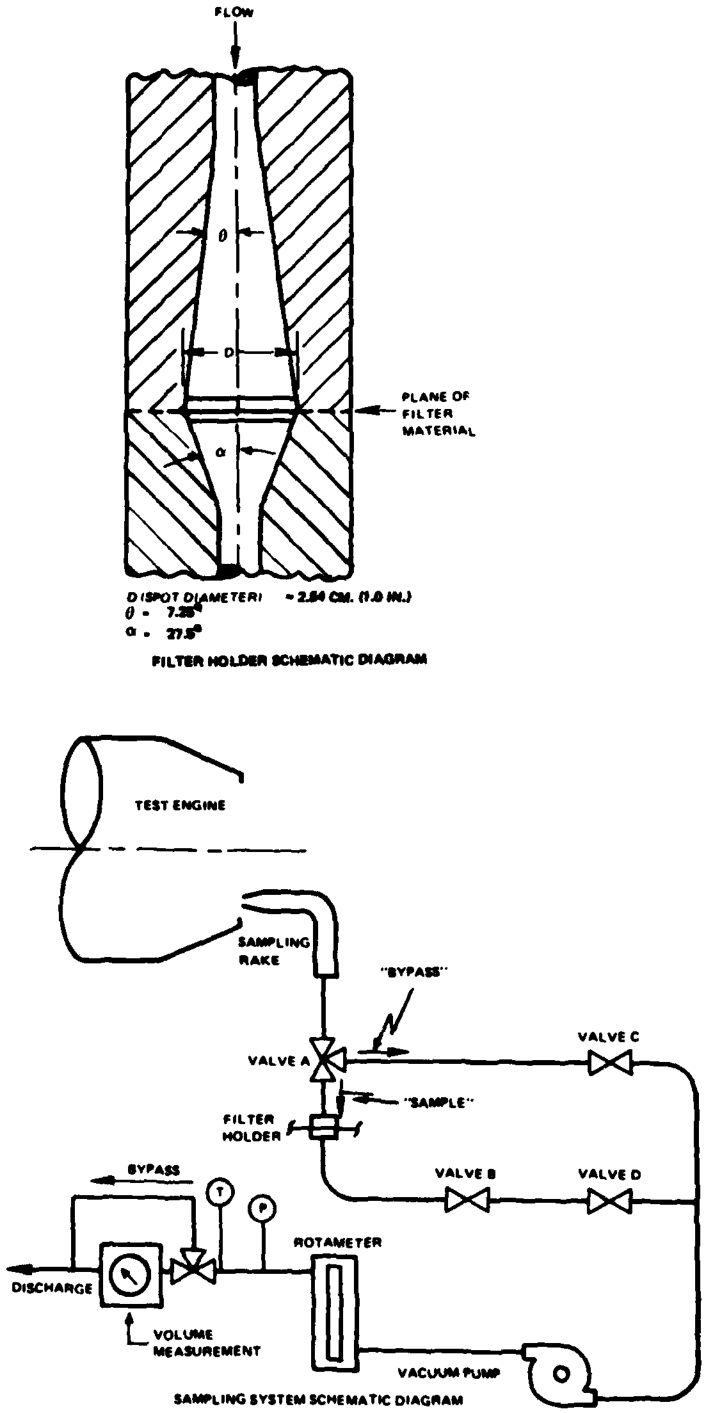


Figure A-8 Details of SAE/EPA Smoke Meter Construction

The unit is designed to minimize variability resulting from operator to operator differences. One of these features is a time controlled, solenoid activated main sampling valve (Valve A, See Figure A-10) having "closed", "sample", and "bypass" positions. This configuration permits close control of the sample size over relatively short sample times. In addition, this timing system operates a bypass system around a positive displacement volume measurement meter to ensure that the meter is in the circuit only when a sample is being collected or during the leak check mode. Other design features include automatic temperature control for the sample line and filter holder, and silicon rubber filter holders with support screens for ease of filter handling.

A Photovolt Model 670 reflection meter with a type-Y search unit conforming to ASA Ph 2.17-1958 "Standard for Diffuser Reflection Density" is used to determine the reflectance of clean and stained filters. A set of Hunter Laboratory reflectance plaques, traceable to the National Bureau of Standards, is used to calibrate the reflectance meter. A computer program is used to calculate the gas sample weight per unit filter area and smoke number.

3. P-6 TEST FACILITY

A. FACILITY DESCRIPTION

The P-6 test stand, one of eight ambient-inlet indoor test cells located at the Pratt & Whitney Aircraft production facility in Middletown, Connecticut, has been fitted with the additional instrumentation and data handling capability required for automatic temperature recording system (ARTS) and low-emission combustor development programs. The facility is equipped with a monorail engine handling system to facilitate movement of the engine into and out of the test cell. A schematic view of the test cell layout is shown in Figure A-9. Figure A-10 shows a front view of a JT9D engine with inlet bellmouth and screen mounted in the test cell. All engine controls, data logging, and computer face equipment are located in the test cell control room. A view of the control console is shown in Figure A-11. The breadboard fuel control computer and peripheral equipment were also installed in the test stand control room. The mobile emissions laboratory was parked outside and to the rear of the test cell while testing was in progress.

A multiple quick disconnect Instrumentation Connection Assembly (ICA) has been incorporated into the facility to reduce the connection time when installing an engine into the test cell. Half of the ICA unit stays in the cell and remains connected to the test stand data acquisition and readout system. The other half is installed on the engine mount frame and instrument lines are connected to the engine during the preparation operation in the marshalling area outside the cell.

A flight-type nacelle is not normally employed for either experimental or production JT9D engine testing. A cylindrical core engine exhaust nozzle is used in place of the plug-type flight design. A pair of bifurcated fan ducts are used in place of the annular fan duct. The fan and core nozzle areas are sized to provide aerodynamic characteristics equivalent to the flight nacelles. The bifurcated fan ducts facilitate installation of special instrumentation and test hardware, and are readily removed for access to the core engine.

Figure A-12 shows the X-686 engine being moved into the test cell on the monorail carrier for a fuel system leak check prior to starting the Phase III Vorbix combustor test program. The leak check is conducted at engine idle power with the fan ducts off. Details of the engine mounting frame, quick-disconnect instrumentation couplings, and cylindrical core engine tailpipe are visible. The engine is shown with the bifurcated fan ducts installed in Figure A-13.

B. DATA ACQUISITION SYSTEMS

The P-6 engine test stand is equipped with two separate and complete data systems. All basic engine performance parameters are determined using the Automatic Production Test Data Acquisition and Control System (APTDAC) which is available to all production test cells. The 2104 Data Acquisition System (ADAPTS) was designed to support ARTS combustor development programs, and is available only in the P-6 test stand at the Middletown Test Facility.

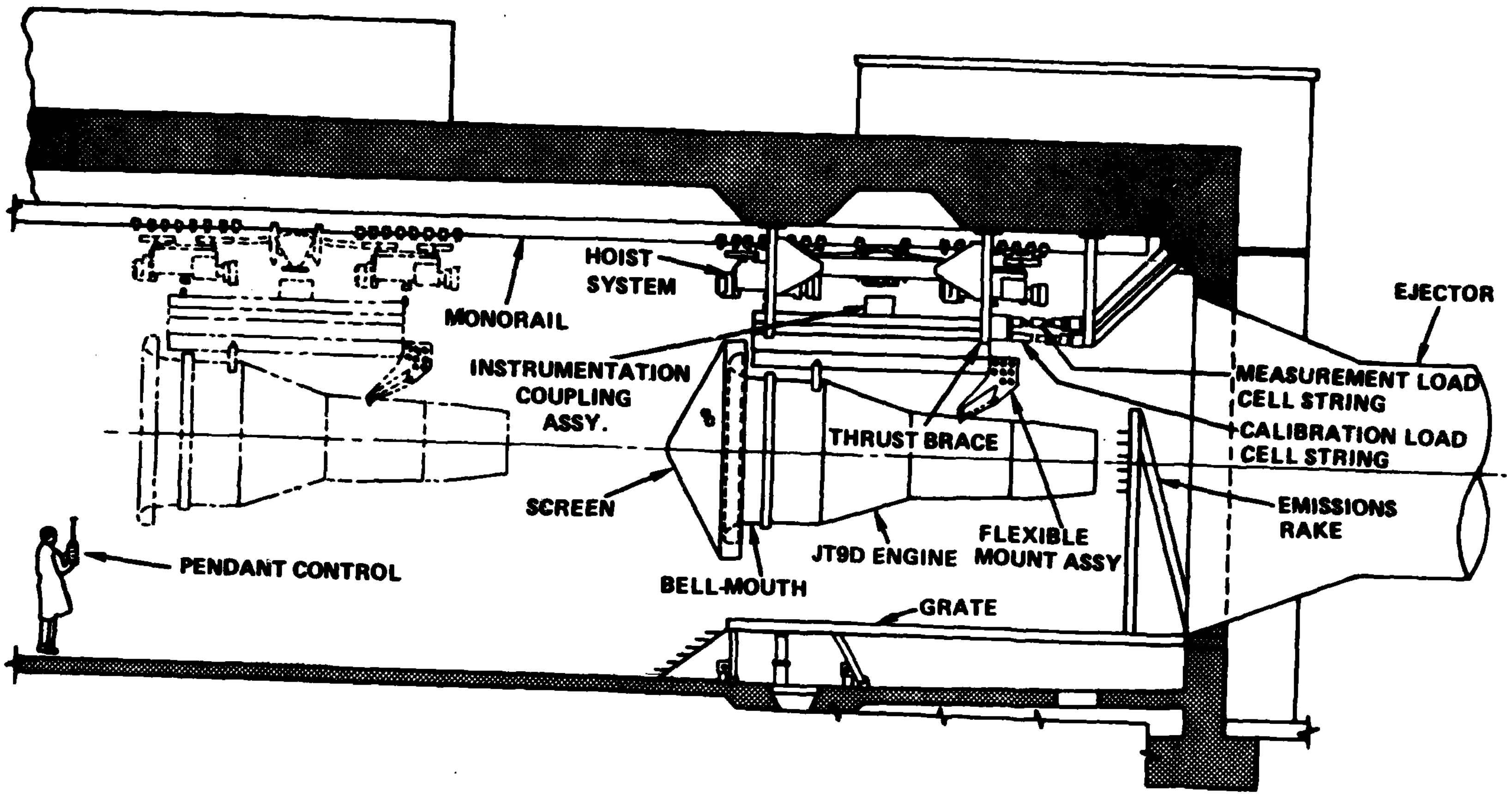


Figure A-9 P-6 Test Cell Layout

Figure A-10 JT9D Engine Mounted in Production Test Cell Showing Inlet Bellmouth and Screen

Figure A-11 Control Cons:›e in P-6 Test Stand Used in Phase III X-686 Engine Tests (76-441-4072-H).

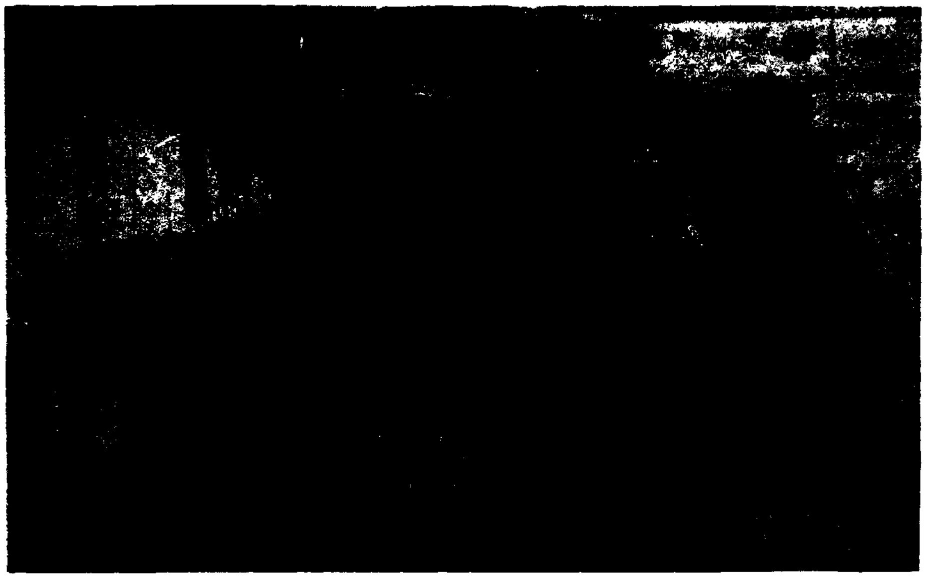


Figure A-12 Right Side View of X-686 Being Moved Into the Test Cell for the Initial Ducts Off Leak Check (CN-57544)

Figure A-13 Experimental Engine, X-686, With Bifurcated Ducts Installed (X-43208)

All aspects of engine performance evaluation – instrumentation hookup, calibration, data logging, performance analysis, data display, and control – have been streamlined by the APTDAC System. APTDAC is an integrated system of sensors, signal conditioning equipment, engine control consoles, digital computers, and cathode-ray tube display devices designed to perform all operating functions automatically. Figure A-14 presents an overview of the system functions.

The APTDAC system is capable of testing eight engines simultaneously – the facility has four computers and each computer can handle two test cells. Each computer is linked to sensing devices in the engine by way of automatic data equipment. Pneumatic and electric transducers measure some 80 different engine operating parameters and relay quantitative data to the computer.

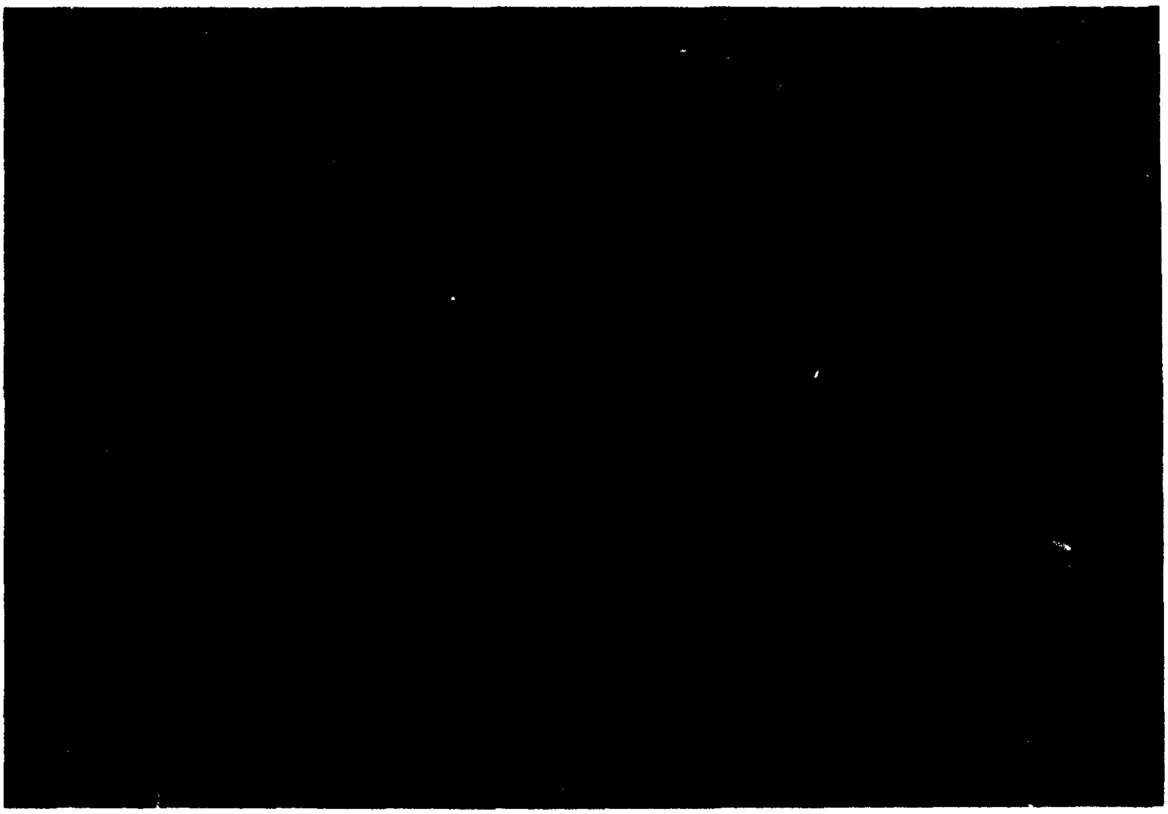


Figure A-14 Automatic Production Test Data Acquisition and Control System Functions

Whether measuring the operating conditions of one or two engines, the assigned APTDAC system computer performs the following acquisition, analysis, and recording tasks:

- Converts the transducer output signals to engineering units
- Corrects the data to standard conditions
- Computes the performance data needed to determine compliance with engine specifications
- Compares selected parameters against established limits and activates an alarm if limits are exceeded
- Displays the data to the operator on a cathode-ray tube
- Provides print-out of the acquired and computed data, on command.

Figure A-15 depicts the flow of data in the system. The APTDAC system is able to scan each variable 10 times, average readings, compute complete engine performance, and print out the results within 15 seconds.

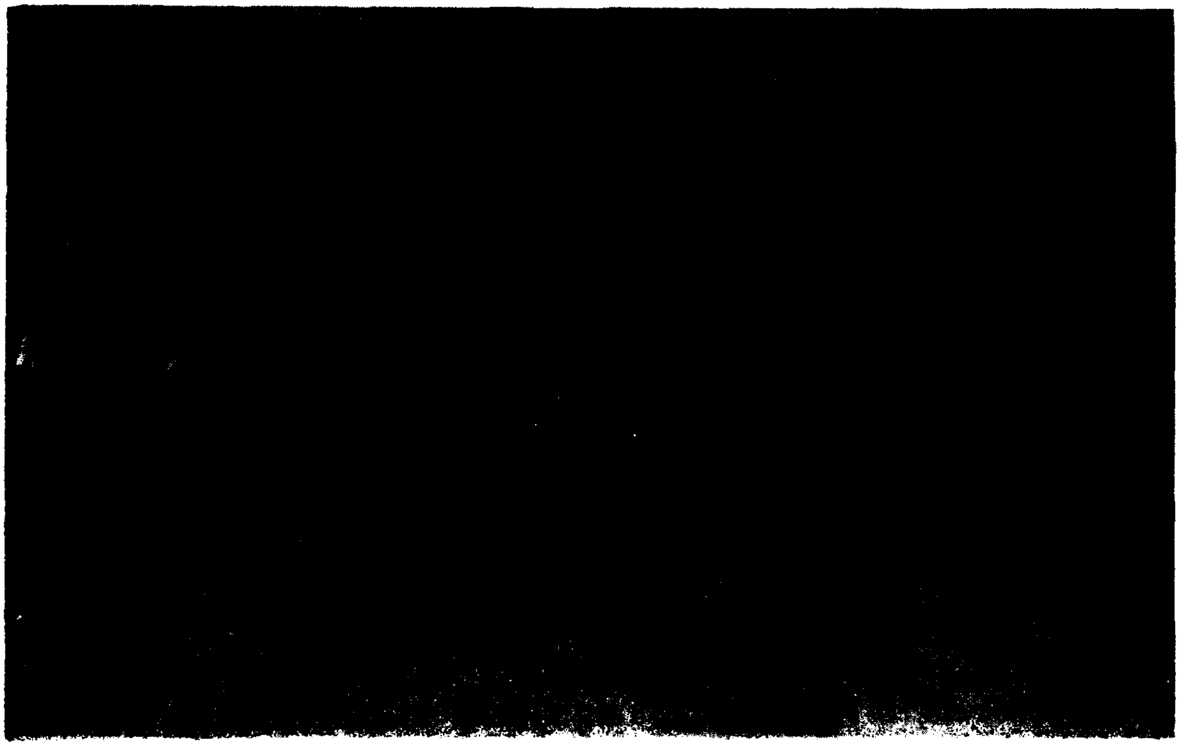


Figure A-15 Automatic Production Test Data Acquisition and Control System Data Flow

Major features built into the computerized engine test system include the capability to conduct tests in either automatic or operator mode, a dynamic update system which allows program changes while running, a debug package, capability for aborting an engine run while in automatic mode when harmful conditions are sensed, and an error message which indicates possibly invalid data.

The 2104 ADAPTS system has the capacity to record up to 1000 millivolt inputs and 384 pressure inputs on five 200 channel scanners and eight 48 port scanning valves. Up to 400 Type B, 500 Type S, and 60 Type K thermocouples, plus two engine speeds, two fuel flows, and 360 pressure parameters can be recorded for any given engine. The remainder of the inputs are used as confidence and reference channels to monitor system accuracy.

The data system has been designed with quick disconnect pressure fittings and electrical connectors to enhance the quick mount capability of the test stand. This provision allows the engine to be installed and connected to the data system in less than two hours. Special features of the data recording system include:

- Channel delete capability
- Three wire guarded system
- OHMS checking capability for thermocouple continuity
- Variable start and end point scan selection
- Manual channel monitoring

C. DATA REDUCTION AND LOGGING SYSTEM

The data reduction and logging fuction for the basic engine performance information is performed by the APTDAC system. All other data, including ARTS thermocouple readings, combustor/diffuser pressure and temperature measurements, and engine emissions data are processed by an on-line Sigma 8 computer located in East Hartford, Connecticut. The data acquisition units tramsmit the data by telephone line to the Sigma 8 computer. Approximately 45 seconds after acquisition, processed information is displayed on an alphanumeric character scope in the test stand control room. The user can select any one of several scope picture (pages) displaying data in engineering units. In addition, the user can view calculated performance parameters based on input data including air flow, Mach numbers, and ideal combustor exit temperature. This real time display of results allows precise matching of test conditions to test program parameters and immediate assessment of the quality of the data.

Editing of the data can be performed via a delete system. Hard copies of all raw data and performance parameters are available at the Sigma 8 computer room in East Hartford as the test is conducted. In addition to hard copies and scope output, the data is recorded and available in other formats.

Raw data is recorded on magnetic tape at the test stand and is available for input to an off-line data reduction computer program for additional processing. Data can be acquired on this magnetic tape unit with or without the Sigman 8 computer being on-line. At the option of the user, raw data can be printed in tabular form on a paper tape printer in the test stand control room. The user can also produce punch cards at East Hartford. All raw data received by the Sigma 8 computer is redundantly recorded on magnetic tape at East Hartford.

In order to minimize the number of entry ports to the Sigma 8 computer occupied by P-6 test stand, special equipment has been installed at the P-6 test stand to permit the 2104 ADAPTS in the test stand control room and the data logging system in the Gas Temperature and Combustion Efficiency (GT & CE) mobile laboratory to time-share the telephone link to the Sigma 8. Priority for transmission of data remains with the 2104 ADAPTS. Upon command from an operator in the P-6 control room, a special electronic switch enables the mobile laboratory to transmit data upon completion of an 2104 ADAPTS transmission. When the Sigma 8 receives the coded signal from the mobile laboratory, it reduces the data and performs the calculations in accordance with instructions in the Mobile Laboratory for Emission Analysis (MOLE) program. The results of the calculations are transmitted back to an interactive scope in the mobile laboratory.

The mobile laboratory operator selects one of three calculation pages to be displayed: an emission data reduction page, a data validation page, and an instrument calibration page. The information displayed when the emission data reduction page is selected includes: fixed identification data, emission concentration, emission index (EI) for each constituent, measured 2 sigma variation of the emission data, carbon basis fuel/air ratio, measured fuel flow, calculated air flow, and calculated combustor exit temperature.

APPENDIX B

EMISSIONS AND PERFORMANCE DATA

The following table present the detailed emissions and performance data obtained during the program. Emissions data were obtained using three different gas sampling techniques as described in Chapter II and Appendix A. The gas sampling rakes used and their symbol designations used on the data tables are presented below:

Symbol	Description
24F	24-Port, 8-Arm, Radial Array, Fixed
ST7	Station 7 Pressure Probe With 8 Radial Pressure Taps
FAA	12-Port, 4-Arm, Diamond Shape

TEST RESULTS FOR CONFIGURATION S27E RUNS 1 AND 2

POINT	THRUST – N	ENGINE INLET PRESSURE – ATM	ENGINE INLET TEMP – °K	HUMIDITY – GH_2O/G AIR	FUEL TEMPERATURE – °K	AIRFLOW, STATION 4 kg/S	AIRFLOW COMBUSTOR kg/S	TOTAL PRESSURE, STATION 4 – ATM	TOTAL TEMPERATURE STATION 4 – °K	FUEL FLOW PILOT – kg/S	FUEL FLOW MAIN – kg/S	IDEAL COMBUSTOR EXIT TEMPERATURE – °K	PATTERN FACTOR	PRESSURE LOSS TOTAL – %
575	205542.	0.989	278.	0.00211	323.	119.2	69.0	21.56	749.	0.595	1.545	1556.	0.0	0.0
576	203678.	0.989	278.	0.00210	324.	109.6	58.5	21.32	746.	0.586	1.506	1542.	0.0	0.0
577	173699.	0.993	277.	0.00212	326.	100.4	81.1	18.99	718.	0.592	1.166	1459.	0.0	0.0
578	173792.	0.993	277.	0.00212	326.	100.5	81.2	18.98	718.	0.603	1.156	1458.	0.0	0.0
579	121595.	0.990	277.	0.00211	331.	82.2	66.4	14.70	665.	0.429	0.766	1301.	0.0	0.0
580	122191.	1.000	277.	0.00211	326.	82.5	66.6	14.75	664.	0.433	0.647	1242.	0.0	0.0
581	60982.	1.004	277.	0.00212	329.	55.6	44.9	9.18	576.	0.326	0.315	1102.	0.0	0.0
582	61071.	1.004	277.	0.00214	328.	55.5	44.8	9.18	575.	0.323	0.317	1101.	0.0	0.0
585	24958.	1.007	277.	0.00211	324.	34.4	27.8	5.18	483.	0.300	0.0	899.	0.0	0.0
586	24495.	1.007	277.	0.00212	325.	33.9	27.4	5.14	482.	0.286	0.0	886.	0.0	0.0
583	14505.	1.007	277.	0.00212	329.	26.2	21.2	3.74	437.	0.203	0.0	823.	0.0	0.0
584	15021.	1.007	277.	0.00212	327.	27.1	21.8	3.92	441.	0.219	0.0	823.	0.0	0.0
591	14367.	1.008	282.	0.00220	324.	26.4	21.3	3.80	448.	0.217	0.0	846.	0.0	0.0
593	14389.	1.008	282.	0.00242	326.	26.3	21.3	3.80	448.	0.217	0.0	846.	0.0	0.0
595	203776.	0.996	281.	0.00267	324.	111.3	89.8	21.59	758.	0.576	1.569	1558.	0.0	0.0
596	203505.	0.996	281.	0.00264	324.	111.1	89.7	21.61	759.	0.574	1.571	1560.	0.0	0.0
599	187336.	1.019	281.	0.00302	324.	105.9	85.5	20.28	741.	0.634	1.315	1511.	0.0	0.0
600	187448.	0.997	281.	0.00302	329.	106.1	85.7	20.28	741.	0.626	1.317	1508.	0.0	0.0
598	175055.	0.998	281.	0.00294	327.	102.0	82.4	19.25	729.	0.609	1.201	1477.	0.0	0.0
597	175051.	0.998	281.	0.00297	327.	102.1	82.4	19.23	729.	0.605	1.191	1472.	0.0	0.0
601	190690.	0.997	281.	0.00312	328.	107.1	86.4	20.52	744.	0.560	1.424	1519.	0.0	0.0
602	191971.	0.997	280.	0.00320	329.	107.5	86.8	20.62	744.	0.590	1.414	1523.	0.0	0.0
603	188328.	0.997	280.	0.00324	328.	106.3	85.8	20.29	740.	0.408	1.566	1517.	0.0	0.0
604	188399.	0.997	280.	0.00331	328.	106.4	85.9	20.30	740.	0.419	1.554	1516.	0.0	0.0
605	151018.	1.000	280.	0.00331	328.	94.0	75.9	17.29	703.	0.523	1.011	1461.	0.0	0.0
606	151001.	1.000	280.	0.00336	323.	94.2	76.1	17.29	702.	0.518	1.016	1460.	0.0	0.0
607	120492.	1.002	280.	0.00328	324.	82.6	66.7	14.67	669.	0.432	0.774	1306.	0.0	0.0
608	121297.	1.002	279.	0.00337	328.	83.1	67.1	14.80	669.	0.446	0.781	1309.	0.0	0.0
609	62766.	1.005	279.	0.00334	331.	56.2	45.4	9.29	582.	0.333	0.323	1113.	0.0	0.0
610	61956.	1.005	279.	0.00338	331.	55.6	44.9	9.23	583.	0.330	0.321	1115.	0.0	0.0
611	61342.	1.005	279.	0.00337	329.	55.8	45.1	9.25	581.	0.260	0.386	1115.	0.0	0.0
612	61787.	1.005	278.	0.00333	328.	56.0	45.2	9.24	580.	0.261	0.393	1111.	0.0	0.0
613	62699.	1.005	276.	0.00335	329.	56.4	45.5	9.26	582.	0.401	0.261	1115.	0.0	0.0
614	62695.	1.004	278.	0.00335	329.	56.3	45.4	9.33	582.	0.399	0.262	1116.	0.0	0.0
615	62712.	1.005	278.	0.00342	331.	56.3	45.5	9.39	582.	0.552	0.109	1115.	0.0	0.0
616	62294.	1.005	279.	0.00341	331.	55.9	45.2	9.31	582.	0.594	0.102	1115.	0.0	0.0
617	13878.	1.008	278.	0.00334	332.	25.6	20.7	3.66	437.	0.204	0.0	827.	0.0	0.0
618	13811.	1.008	278.	0.00337	329.	25.7	20.7	3.66	437.	0.206	0.0	828.	0.0	0.0
619	16791.	1.008	277.	0.00329	326.	28.4	23.0	4.10	451.	0.234	0.0	848.	0.0	0.0
620	16738.	1.008	278.	0.00331	326.	28.4	23.0	4.10	451.	0.233	0.0	847.	0.0	0.0
621	26408.	1.008	278.	0.00338	324.	35.7	28.8	5.40	491.	0.320	0.0	916.	0.0	0.0
622	26052.	1.008	279.	0.00340	325.	35.7	28.8	5.36	490.	0.316	0.0	911.	0.0	0.0

POINT	REFERENCE VEL – m/s	FUEL AIR RATIO COMBUSTOR METERED STATION 5	FUEL AIR RATIO PILOT	FUEL AIR RATIO CARBON BALANCE STATION 7	F/A CB / F/A MET @ STATION 7	CO_2 – %	CO (EI) AS MEASURED	THC (EI) AS MEASURED	NO_x (EI) AS MEASURED	GAS SAMPLE COMBUSTION EFFICIENCY	SAE SMOKE NO.	NO_x (EI) CORRECTED FOR HUMIDITY & PRESSURE	CO (EI) CORRECTED FOR PRESSURE	THC (EI) CORRECTED FOR PRESSURE	RAKE	COMMENTS (1)
575	50.	0.0241	0.0067	0.0195	1.02	3.96	1.70	0.06	13.82	99.95	30.60	12.46	1.78	0.06	24F	SLTO
576	50.	0.0237	0.0066	0.0199	1.06	4.03	1.91	0.12	13.92	99.96	0.0	12.51	2.02	0.12	ST7	SLTO
577	49.	0.0217	0.0073	0.0182	1.06	3.70	1.89	0.09	12.55	99.95	0.0	11.19	2.03	0.10	ST7	CLIMBFN
578	49.	0.0217	0.0074	0.0177	1.03	3.60	1.68	0.11	12.36	99.95	21.30	11.03	1.90	0.11	24F	CLIMBFN
579	48.	0.0186	0.0065	0.0151	1.05	3.07	3.69	0.14	8.09	99.90	0.0	7.20	3.97	0.15	24F	SUBCLIMB
580	48.	0.0162	0.0065	0.0152	1.06	3.09	4.98	0.15	8.12	99.89	0.0	7.20	4.43	0.16	ST7	SUBCLIMB
581	45.	0.0143	0.0073	0.0116	1.33	2.37	11.60	0.42	4.80	99.68	0.0	4.23	12.78	0.47	24F	APPROACH
582	45.	0.0143	0.0072	0.0114	1.01	2.32	13.25	0.48	4.84	99.64	0.0	4.25	14.65	0.53	ST7	APPROACH
585	42.	0.0106	0.0106	0.0086	1.02	1.80	5.19	0.32	4.51	99.84	0.0	4.02	5.55	0.34	24F	IDLE+
586	41.	0.0104	0.0104	0.0086	1.00	1.76	5.92	0.34	4.38	99.82	0.0	3.91	6.34	0.36	ST7	IDLE+
583	46.	0.0098	0.0098	0.0081	1.04	1.64	18.87	1.17	2.81	99.42	0.0	2.47	20.75	1.29	24F	IDLE
584	40.	0.0100	0.0100	0.0082	1.04	1.66	20.71	1.61	2.74	99.33	0.0	2.40	23.18	1.80	ST7	IDLE
591	40.	0.0102	0.0102	0.0094	1.16	1.91	15.22	0.61	3.11	99.57	0.0	2.84	15.62	0.63	FAA	IDLE
593	40.	0.0102	0.0102	0.0087	1.07	1.76	15.78	0.95	3.00	99.52	0.0	2.75	16.20	0.98	ST7	IDLE
595	51.	0.0239	0.0064	0.0206	1.05	4.06	1.49	0.01	14.92	99.96	29.40	13.45	1.52	0.01	FAA	MAXFN
596	51.	0.0239	0.0064	0.0197	1.04	3.99	1.65	0.06	14.67	99.95	0.0	13.59	1.67	0.06	ST7	MAXFN
599	50.	0.0228	0.0074	0.0194	1.07	3.93	1.32	0.17	14.15	99.95	0.0	13.13	1.36	0.17	FAA	CLIMB
600	50.	0.0227	0.0073	0.0194	1.08	3.94	1.47	0.20	14.05	99.94	0.0	13.03	1.50	0.21	ST7	CLIMB
598	50.	0.0220	0.0074	0.0182	1.04	3.70	1.46	0.13	13.64	99.95	22.00	12.60	1.50	0.13	FAA	CLIMB
597	50.	0.0218	0.0073	0.0185	1.07	3.76	1.52	0.09	13.21	99.95	0.0	12.23	1.56	0.09	ST7	CLIMB
601	50.	0.0231	0.0065	0.0193	1.06	3.93	1.59	0.04	13.36	99.96	23.50	12.42	1.63	0.04	FAA	PILOTFSP
602	50.	0.0231	0.0068	0.0196	1.07	3.97	1.68	0.04	13.52	99.96	0.0	12.57	1.73	0.04	ST7	PILOTFSP
603	50.	0.0230	0.0048	0.0190	1.04	3.85	2.81	0.03	12.02	99.93	35.10	11.16	2.90	0.03	FAA	PILOTFSP
604	50.	0.0230	0.0049	0.0194	1.07	3.93	2.72	0.04	12.40	99.93	0.0	11.53	2.81	0.04	ST7	PILOTFSP
605	50.	0.0202	0.0069	0.0170	1.06	3.46	2.07	0.05	10.66	99.95	17.70	9.84	2.17	0.05	FAA	PILOTFSP
606	50.	0.0202	0.0066	0.0173	1.08	3.51	2.09	0.14	10.41	99.93	0.0	9.59	2.20	0.15	ST7	PILOTFSP
607	49.	0.0181	0.0065	0.0149	1.14	3.04	3.84	0.28	8.31	99.88	0.0	7.65	4.04	0.30	FAA	
608	49.	0.0182	0.0066	0.0154	1.07	3.12	3.86	0.32	8.08	99.87	0.0	7.41	4.11	0.34	ST7	
609	46.	0.0145	0.0073	0.0124	1.07	2.51	12.62	0.39	5.11	99.66	0.0	4.64	13.03	0.42	FAA	APP.PFSP
610	46.	0.0145	0.0073	0.0121	1.05	2.45	12.00	0.23	4.97	99.69	0.0	4.55	12.84	0.25	ST7	APP.PFSP
611	46.	0.0145	0.0056	0.0127	1.10	2.47	23.88	1.20	4.39	99.30	0.0	3.99	25.62	1.30	FAA	APP.PFSP
612	46.	0.0144	0.0058	0.0122	1.06	2.47	18.76	0.85	4.57	99.46	0.0	4.15	20.33	0.92	ST7	APP.PFSP
613	46.	0.0145	0.0068	0.0124	1.06	2.52	9.35	0.26	6.34	99.75	0.0	5.75	10.17	0.29	FAA	APP.PFSP
614	46.	0.0145	0.0068	0.0115	1.00	2.35	9.02	0.20	6.73	99.77	0.0	6.11	9.78	0.21	ST7	APP.PFSP
615	45.	0.0145	0.0121	0.0120	1.04	2.44	5.61	0.14	9.32	99.65	0.0	8.45	6.17	0.15	FAA	APP.PFSP
616	45.	0.0145	0.0123	0.0111	0.96	2.26	5.93	0.19	8.19	99.84	0.0	8.08	6.42	0.20	ST7	APP.PFS
617	40.	0.0099	0.0099	0.0089	1.15	1.81	21.14	1.53	2.87	99.33	0.0	2.62	22.61	1.65	FAA	IDLE
618	40.	0.0100	0.0100	0.0081	1.03	1.65	22.75	2.14	2.82	99.22	0.0	2.57	24.52	2.31	ST7	IDLE
619	41.	0.0102	0.0102	0.0092	1.13	1.97	14.20	0.85	3.18	99.57	0.0	2.60	15.32	0.91	FAA	IDLE
620	41.	0.0101	0.0101	0.0083	1.04	1.70	14.13	0.98	3.07	99.56	0.0	2.80	15.24	1.05	ST7	IDLE
621	42.	0.0111	0.0111	0.0099	1.13	2.07	4.94	0.14	4.69	99.67	0.0	4.29	5.27	0.15	FAA	IDLE
622	42.	0.0113	0.0110	0.0089	1.02	1.81	4.77	0.23	4.52	99.86	0.0	4.15	5.06	0.24	ST7	IDLE

APPENDIX C

REFERENCES

1. Roberts, A., Fiorentino, A., and Greene, W., "Experimental Clean Combustor Program," Phase III Final Report, NASA CR-135253, October 1977.

APPENDIX D

METRIC CONVERSION FACTORS

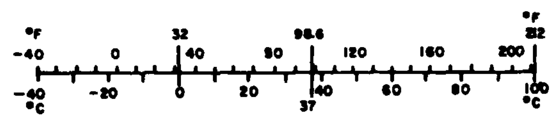
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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